DEVELOPING A TECHNOLOGY SELECTION FRAMEWORK FOR NUCLEAR-RENEWABLE HYBRID ENERGY SYSTEMS

by

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ABSTRACT

DIANA GRANDAS. Developing a technology selection framework for nuclear-renewable hybrid energy systems. (Under the direction of DR. MICHAEL SMITH)

Nuclear-renewable hybrid energy systems (N-R HESs) are being considered globally to optimize the benefits of and mitigate challenges associated with nuclear and variable renewable energy technologies. Organizations interested in adopting N-R HESs must make careful decisions to determine an optimal selection of generation resources and end-use loads. Many factors can influence preferred hybrid energy system design selection, including alignment with business mission, carbon emissions reductions, capital and operational costs, location, environmental impact, and technology maturity and scalability. A growing set of literature evaluates the viability of N-R HES configurations, focusing on assessing optimal N-R HES configurations based on economic performance. However, multiple factors, including those beyond economics, are often highly critical to decision makers. Thus, the performance of an N-R HES configuration on a single factor cannot adequately determine if the system is the overall preferred choice. A multi-criteria technology selection framework, where multiple criteria are considered and prioritized from the inception of the selection process, can facilitate the identification of optimal combinations of energy supply resources and end-use loads to meet the desired outcomes of an N-R HES. This thesis proposes a novel multi-criteria decision making methodology that guides the selection of energy generation and end-use options in a hybrid energy system with multiple generation resources (e.g., nuclear energy) and serves multiple loads. This work also describes results from a case study of example NR-HES configurations generated from the selection framework. System economic performance and generation option sizing requirements are analyzed using the HOMER Pro software package. Power flow analysis of example systems is completed via MATLAB-Simulink.

DEDICATION

I dedicate this thesis to my dad and brother, Oscar and Sebastián, who have provided me with endless encouragement, strong motivation, and models of perseverance throughout this thesis work, my academic career, and my life. I am also grateful for the abundance of friends and colleagues who have supported me through this academic pursuit. This work is in loving memory of my mother, Jennifer, whose unbridled spirit and dedication to her passions built the foundation for the student, researcher, and person I am today.

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LIST OF ABBREVIATIONS

°C degree Celcius

AC alternating current

AR advanced reactor

CAPEX capital expenditures

CFE carbon-free energy

CO_2 carbon dioxide

CSP concentrated solar power

DC direct current

DG diesel generator

DOE U.S. Department of Energy

EPRI Electric Power Research Institute

FLiBe fluoride/lithium beryllium

GW gigawatt

HES hybrid energy system

HTGR high temperature gas reactor

IES integrated energy system

IRR internal rate of return

kg kilogram

kW kilowatt

kWh kilowatt hour

LCOE levelized cost of energy

LWR light water reactors

m meter

MED multi-effects distillation

MSF multi-stage flash

MSR molten salt reactor

MW megawatt

MWh megawatt hour

N-R HES nuclear-renewable hybrid energy system

NPC net present costs

NPP nuclear power plant

NPV net present value

O oxygen

OPEX operating expenditures

PEM polymer electrolyte membrane

PV photovoltaic

RO reverse osmosis

RTE round trip efficiency

SMR small modular reactor

SOC state of charge

TES thermal energy storage

TRL technology readiness level

U.S. United States

USD United States dollar

W Watt

CHAPTER 1: INTRODUCTION

1.1 The Role of Nuclear-Renewable Hybrid Energy Systems

As population and economic growth, improved living standards, and industrial needs drive energy demand increases across all economic sectors, deployment of new energy generation capacity is set to increase to meet said needs [1]. Concurrently, global recognition of the current and future impacts of climate change has initiated a transition from carbon-intensive to low-carbon energy supply resources. Many governments made commitments towards decarbonization as part of the Paris Agreement, which aims to keep "the increase in the global average temperature to well below 2°C above pre-industrial levels" and implement strategies "to limit the temperature increase to 1.5°C above pre-industrial levels" [2]. For example, the U.S. has pledged to achieve 50-52% net greenhouse gas emissions reductions based on 2005 levels by 2030 [3]. Utilities, states, energy companies, and other commercial and industrial energy consumers have set net-zero targets, many requiring net-zero operations around the 2050 time frame [4].

Prompted by these decarbonization goals, the energy system is already transitioning to include more low-carbon resources. For example, solar photovoltaic (PV) and wind-based renewable energy were rapidly deployed in recent years and are set to continue this deployment trend [5]. However, these variable renewable resources face challenges as they only produce energy during certain times of day or during favorable climate conditions. In times of favorable conditions for renewables, the system's total energy generation may exceed demand, and the renewable output is curtailed, wasting resources. With fossil-based base load energy generation being retired, attention on and development of nuclear systems is increasing, as it can serve as a firm resource to balance the variable nature of solar and wind resources [6, 7]. However, nuclear energy deployment is challenged with high capital costs and licensing and construction timelines, though advanced reactor designs may mitigate some of these challenges.

Nuclear-renewable hybrid energy systems (N-R HESs) are proposed to maximize benefits of and overcome challenges associated with each energy generation technology in isolation [8, 9]. Hybrid energy systems (HESs) closely coordinate multiple types of energy generation resources to serve electrical and/or thermal energy to one or multiple loads (Figure 1.1). In the context of a carbon-free energy system, nuclear resources with high capacity factors can be coupled with renewable resources in service of variable and static loads to optimize each technology's benefits. This integrated system can support balancing grid loads while decarbonizing other energy needs such as industrial electricity (e.g., data centers) or industrial heating, hydrogen production, or desalination. For example, when grid demand is high or cannot be met by renewable output alone, most energy output from the hybrid system can be directed to electricity generation for the grid. In times of low grid demand or high renewable output, electrical or thermal energy from the nuclear resource can be diverted to non-power grid loads, reducing the risk of curtailing renewables. Thermal energy storage can also be used to store excess energy from thermal generation resources when renewable resources are producing abundant energy. Additionally, advances in nuclear technology, like the development of small modular reactors (SMRs), allow nuclear systems to act more flexibly and couple closer with variable renewables.

1.2 Project Motivation and Current Challenges

Like the decision to adopt or deploy any energy technology, system, or infrastructure, organizations interested in N-R HESs must make rigorous, informed decisions to determine optimal system designs. Many factors can influence hybrid energy system design, including alignment with business mission, carbon reduction potential,

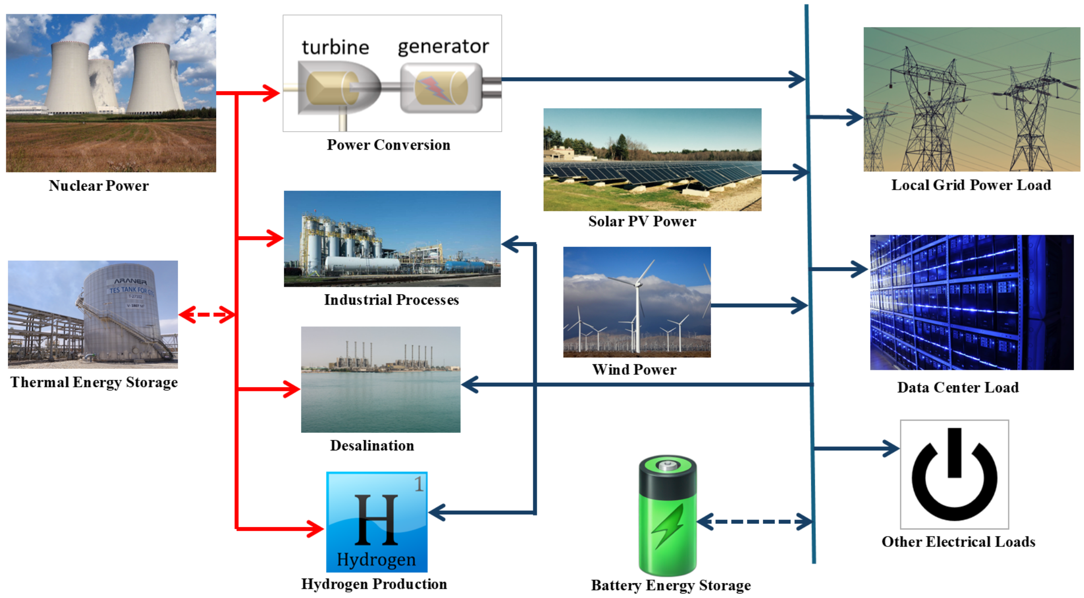


Figure 1.1: General schematic of nuclear-renewable hybrid energy systems and options for serving multiple thermal (red lines) or electrical (blue lines) loads or storage systems (dashed lines) to optimize the benefits of nuclear and renewables and reduce challenges that accompany each technology.

capital and operational costs, policy incentives, location, social and environmental considerations, scalability, flexibility, land use, technology maturity, and/or technical compatibility with preferred energy generation resources. Challenges for designing and implementing a hybrid energy system include optimizing system features at different temporal and spatial scales and managing preferences of various stakeholders. A multi-criteria technology selection framework can facilitate the identification of optimal combinations of energy supply resources and end-use loads to meet the desired outcomes of an N-R HES. Once candidate system technology configurations are selected through a high-level selection framework based on multiple criteria, a detailed techno-economic analysis assists in confirming technical and economic feasibility and finalizing decisions.

1.3 Thesis Statement and Research Contributions

This work will propose a multi-criteria decision making methodology for NR-HES design. Specifically, this methodology guides the selection of energy generation and end-use options in a hybrid energy system that includes multiple generation resources, including nuclear energy, serving multiple loads. This framework will provide a mechanism for decision makers to prioritize and weigh relevant evaluation criteria and compare the performance of energy generation and end-use options on these criteria. After a selection methodology is proposed, a case study will be performed, selecting one combination of energy generation and end-use options and evaluating technical and economic feasibility. The system's economic performance will be assessed using the HOMER Pro software package. System behavior and power flows will be analyzed via MATLAB-Simulink. The outcomes of this project can be used to evaluate the performance of potential configurations and technology candidates in future hybrid energy systems.

1.4 Thesis Organization

The structure of the remainder of this report is as follows: Chapter 2 provides further background on the topic of hybrid energy systems and insights from a review of relevant literature. Chapter 3 describes the technology selection framework and provides an initial evaluation of select technologies on a set of example evaluation criteria. Chapter 4 describes the case study down-selection example. Chapter 5 details the techno-economic evaluation of an example nuclear-renewable hybrid energy system configuration using HOMER Pro and MATLAB-Simulink. Chapter 6 provides conclusions of this work.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

2.1 Chapter Introduction

N-R HESs are being proposed to optimize the mutual benefits of component technologies to serve various decarbonized systems. This chapter provides an overview of N-R HESs, operating modes, descriptions of potential energy generation technologies and energy end-uses typically considered for N-R HESs, and the current state of development and deployment. This chapter concludes with a discussion of existing methods of selecting optimal technology configurations for an N-R HES to motivate novel contributions in this research.

2.2 Overview of Nuclear-Renewable Hybrid Energy Systems

Hybrid energy systems involve close coupling of multiple energy generation resources to serve one or more end-use loads. N-R HESs are, in particular, being considered to optimize both nuclear and renewable resources to provide carbon-free energy efficiently and reliably. N-R HESs are often proposed to decarbonize industrial processes while simultaneously providing grid-balancing benefits. Coordinated operation allows electric or thermal energy to be diverted between end-uses depending on each end-use's temporally varying demand needs.

2.2.1 Configurations and Modes of Operation

HESs typically take one of three overarching configurations [9]:

1. Single generation resource technology serving multiple end-use loads

2. Multiple generation resource technologies serving a single end-use load

3. Multiple generation resource technologies serving multiple end-use loads

HES types can also be distinguished based on whether their components and loads are tightly or loosely coupled. This project is primarily concerned with tightly coupled HESs with multiple resources and end-use loads, as this overarching configuration offers the opportunity to coordinate nuclear and renewable energy resources via optimal operational modes. For example, if the N-R HES only served the power grid, load following could only be accomplished by ramping up or down the nuclear power plant (NPP), as renewables cannot be ramped easily. For NPPs whose operation and maintenance are optimized for continuous full power production (like those currently operating in the U.S.), ramping the nuclear resource may not be an ideal operational mode as it may reduce plant efficiency and could strain mechanical equipment. However, if the system serves another load alongside a power grid load, either electrical or thermal energy can be diverted between end-use loads while maintaining near full-power NPP operation. In particular, if multiple small modular reactors (SMRs) are used in place of a large reactor, during times of high renewable penetration, thermal or electric energy from a subset of modules can be diverted to the non-grid resource while the other modules continue to service the grid [10]. When renewable production is low, and grid demand is high, most or all the modules can be set to provide energy in service to the grid. SMRs, along with other generation technology options for N-R HES, will be described in the following subsection.

2.2.2 Energy Generation Technology Options for N-R HESs

This project considers N-R HESs that include nuclear coupled with one or more renewable energy technologies as the generation resources, with or without an electric or thermal energy storage system. These generation options are described below.

2.2.2.1 Nuclear Energy

Nuclear energy is a prominent carbon-free energy resource across the globe. Per Albert Einstein's equation for mass-energy equivalence ($E = mc^2$), any small change in mass m in a system equates to a large release of energy E (since c, the speed of light, is a very large number). In nuclear energy plants, the process of fission occurs, where uranium nuclei are split, releasing energy stored in the atomic nuclei. As they split, the sum of the masses of resulting lighter nuclei is less that the mass of the original uranium nucleus. Thus, per the mass-energy equivalence equation, massive amounts of energy are released. This energy is carried by neutrons, which are released when the uranium nucleus splits. These neutrons go on to split more uranium atoms, prompting a chain reaction inside the nuclear reactor, carefully controlled by retractable control rods that absorb excess neutrons. These neutrons also heat cooling water, resulting in steam that is directed to a turbine for electricity generation. In 2023, NPPs generated 18% of the total electricity generated in the U.S. [11] Globally, nuclear energy comprised over 9% of electricity generation in 2022 [12].

Currently, most commercially operational NPPs are large, 1,000 megawatt (MW) light-water reactors (LWRs), meaning light-water, or normal water, is used as a coolant and neutron moderator. However, advances are being made to develop advanced reactor (AR) technologies, or reactor technologies that offer significant improvements, compared to those operating in the U.S. as of December 2020 [13]. Examples of ARs include light-water SMRs, high-temperature gas reactors (HTGRs), molten salt reactors (MSRs), and liquid metal fast reactors [14]. The "significant improvements" provided by different AR designs include advanced safety features, higher output temperatures (and thus have higher efficiency and ability to provide process heat), and smaller sizes. Nuclear reactor sizes can be defined per Table 2.1 [13].

Table 2.1: Size Range Definitions for Nuclear Reactors

Size	Operating MW (thermal)	Output MW (electric)
Micro	$\leq$150	$\leq$50
Small	150 $\leq$ 900	50$\leq$ 300
Medium	1000 $\leq$ 1800	300$\leq$ 600
Large	>1800	>600

Advanced reactor technologies are particularly promising for use in N-R HESs. For example, using multiple SMR modules in a single facility can allow electric or thermal energy to be diverted between end-uses at the balance of plant stage, avoiding the need to ramp the reactor core when more or less energy is required. When grid demand is high, the power output from the full SMR fleet can be directed towards the grid. When grid demand is low, energy output from a subset of modules can be directed to non-grid end-uses while the other modules continue to serve the grid [10]. Alternatively, power could be diverted in or after the balance of plant just before power conversion for thermal energy, or after power conversion for electrical energy. Higher temperature reactor technologies also lend themselves to thermal energy end-uses, such as industrial process heat, desalination, and hydrogen production.

2.2.2.2 Solar Photovoltaic Energy

Solar energy technologies harness solar radiation incident on the surface of the Earth, converting the incident energy into usable energy. Solar photovoltaic (PV) technologies, in particular, absorb solar energy and convert it to electrical energy through semiconducting materials [15]. Over the last decade, solar PV has led renewable energy resources with the largest annual electricity capacity additions, a trend likely to continue in the near future [5, 16]. As a generation technology easily operable as a distributed energy resource or a utility-scale generation resource, solar PV is often considered in HES design.

Because power output from a solar PV array depends on the solar radiation incident on the panel surface, output varies daily and throughout the year. The power output of a solar array can be calculated via Equation (2.1) [17]:

$$P_{PV} = f_{PV} Y_{PV} \frac{I_T}{I_S}, \tag{2.1}$$

where f_{PV} is the PV derating factor, Y_{PV} is the rated capacity of the PV array (in kW), I_T is the global solar radiation incident on the surface of the PV array, and I_S is 1 kW/m^2, the standard radiation used to rate the capacity of PV arrays. Air density is typically taken at standard temperature and pressure conditions as 1.225 kg/m^3. Equation (2.1) will be used during the modeling case study portion of this work as described in Chapter 4.

2.2.2.3 Wind Energy

Wind energy is another type of variable renewable energy technology that is being rapidly deployed. Wind turbines capture the kinetic energy of the wind, converting it to the kinetic energy of the turbine blades and rotor, and then generating electrical energy via a generator. Because power output scales linearly with number of turbines, wind turbines can be used as smaller-scale distributed resources or, in the case of large wind farms, as a utility-scale resource. Power output from a single wind turbine can be described as:

$$P_{wind} = \eta_{turb} \rho_{air} v_{wind}^3 A, \tag{2.2}$$

where η_{turb} is the wind turbine efficiency, ρ_{air} is the air density at the wind turbine hub height, v_{wind} is the wind speed at the wind turbine hub height, and A is the cross-sectional area swept by the turbine blades. If the turbine had blades with radius r, A would equal πr^2.

2.2.2.4 Diesel Generators

While not a carbon-free energy resource, diesel generators (DGs) are currently used for backup energy supply in residential and commercial systems and are included as options in some instances of microgrid or hybrid energy system planning. Even if a system planner intends to have the microgrid or hybrid energy system running on carbon-free resources most of the time, a DG can be implemented simply as a resilience or energy security feature. DGs are also frequently used in remote locations where access to a central power grid may be limited or unavailable. Additionally, DGs may be preferred in locations unfavorable to certain renewable resources. For example, solar PV is likely unfavorable in very northern locations where annual average solar irradiance is very low [18].

Important considerations for DGs are the amount of fuel used and associated carbon dioxide emissions. The amount of diesel fuel used by the generator per unit time is defined as [17, 19]:

$$F_{DG} = F_O Y_{DG} + F_1 P_{DG}, \tag{2.3}$$

where F_O is the no-load fuel consumption of the generator divided by its rated capacity and F_1 is the marginal fuel consumption of the generator in units of fuel per hour per kW of generator output [19]. These coefficients are specific to the generator type and are typically given by the manufacturer. Y_{DG} is the DG's rated capacity, and P_{DG} is the DG's actual power output. An estimated 10,180 grams of CO_2 are emitted for every gallon of diesel consumed [20].

2.2.2.5 Energy Storage

Energy storage systems are being deployed to complement variable renewable energy resources by storing excess energy during high production and dispatching during times of low production. While some HESs can provide enough capacity and flexibility in operation and dispatch modes to not require energy storage, storage can supplement generation flexibility. Like DGs, energy storage can provide additional energy security in case the NPP or other base load energy resource comes offline or if energy demand exceeds total generation resources.

Energy storage technologies can store and produce various forms of energy. For example, battery energy storage is a popular technology for storing and dispatching electrical energy. 40 GW of battery storage were added in 2023, doubling additions from 2022 and resulting in a global battery energy storage capacity of 85 GW. Lithium ion batteries largely dominate the battery energy storage market [21]. Other storage technologies like pumped hydro storage or flywheels store potential or kinetic energy, respectively, and dispatch electrical energy. Thermal energy storage technologies, which store and dispatch heat, are currently in use in concentrated solar power plants and have high potential value for coupling with nuclear resources [22]. Examples of thermal energy technologies include molten-salt sensible heat storage, solid-based storage, or latent heat storage systems [23].

2.2.2.6 Other Energy Generation Resources

There are many other existing and emerging energy technologies that could be used in HESs that will not be explored in detail in this project. For example, hydroelectric systems (i.e., hydropower dams) provide clean power and account for 6% of electricity generation, though new deployments may be limited due to strict location and natural resource requirements. Marine hydrokinetic resources, such as tidal energy turbines, are emerging energy technologies that could be most relevant to systems serving desalination plants. However, marine hydrokinetic technologies' early TRL limits the ability to estimate performance on certain metrics. Thus, these technologies are not included in this project. Fusion energy is another emerging energy generation technology that promises abundant carbon-free energy by harnessing the energy released when two light nuclei (typically hydrogen isotopes) combine (or fuse) into a heavier nucleus. Although technical development is accelerating and the fusion private sector is growing rapidly, a fully operational fusion pilot plant has yet to be demonstrated, and one may not be for years or decades to come. Thus, due to its early technological maturity and uncertainty of fusion power plant performance characteristics, it is outside the scope of this project to include fusion in the technology selection framework as given. Geothermal energy resources are also not considered in this research due to these resources requiring geologically favorable sites, which limits possible locations of deployment compared to other technologies in this analysis. However, since this project does present a generic technology selection framework methodology, the framework can be easily modified to include additional existing or emerging technologies as a framework user deems necessary.

2.2.3 End-Use Loads

Depending on the use case, N-R HESs can serve a power grid load, a non-power grid energy end-use, or both. In the case of an N-R HES serving multiple end uses, non-grid energy end uses can act as a deferrable that can be powered with excess energy when the primary demand is fulfilled. Examples of these non-grid loads are described below.

2.2.3.1 Desalination

Desalination is the process by which salts or other minerals are removed from water, making it safe for human consumption. These systems, and the energy generation resources used to power them, must be located in a coastal region. Multiple technologies exist for desalination, requiring either electrical or thermal energy. For example, the following desalination processes are particularly compatible with nuclear energy [24, 25]:

- **Multi-stage flash (MSF):** A thermal energy-based desalination process based on distillation principles through multi-stage chambers whereby water is first heated under high pressure, then routed to a chamber where pressure is quickly reduced and the water boils rapidly, or "flashes". This process continues for multiple chambers and vapor from the "flashes" is condensed into desalinated water.

- **Multi-effect distillation (MED):** In the first chamber, low-pressure steam runs through a tube, heating and boiling feedwater. The resulting vapor is used to heat the subsequent chamber, boiling additional sprayed feedwater and allowing desalinated water to condense from the vapor in the tube. This process continues for multiple effects, or stages. MED is another example of a thermal energy-based desalination process

- **Reverse osmosis (RO):** A semi-permeable membrane separates salt and other contaminants from feedwater after external pressure is applied to overcome osmotic pressure. This approach uses electricity as the main type of input energy. RO is generally classified as the most energy-efficient process for desalination.

2.2.3.2 Hydrogen Production

Global interest in hydrogen as a low-carbon energy carrier is increasing for decarbonizing industrial processes, transportation, or gas turbines for electric power generation. Hydrogen also benefits from its ability to serve as energy storage: hydrogen can be produced during times of excess energy, stored, and then used as demand requires. While certain hydrogen production processes require the combustion of fossil fuels, production via electrolysis can allow for renewable or nuclear-produced electricity to be used to create clean hydrogen. There are various mechanisms for hydrogen production potentially compatible with N-R HESs. Of particular interest are electrolyzers, which consist of an anode and cathode separated by an electrolyte and use electricity to produce the hydrogen [26, 27, 22, 28]:

- **Polymer electrolyte membrane (PEM) electrolyzers:** Water splits to oxygen and hydrogen ions at the anode. Electrons move through an external circuit while hydrogen ions move across the PEM to the cathode. Hydrogen ions combine with electrons from the external circuit to form hydrogen gas. PEM is a low-temperature (<100 °C) process.

- **Alkaline electrolyzers:** Two electrodes are immersed in an alkaline water electrolyte. Hydroxide ions are transported through the electrolyte and hydrogen produced at cathode. Alkaline electrolysis is a low temperature (<100 °C) process.

- **Solid oxide electrolyzers:** Steam is fed into the cathode, and an electric potential is applied. Water then dissociates into hydrogen and oxygen. Oxygen ions pass through solid membrane to anode to form O_2 and generate electrons. This process requires high temperatures (700-800 °C) and could leverage thermal energy from advanced nuclear reactors with higher output temperatures.

2.2.3.3 Industrial Process Heating and Industrial Electricity Loads

Process heating is used to produce, treat, or alter manufactured goods and is used in almost all manufacturing processes. These manufacturing processes include material fabrication, component assembly, electronics production, chemical manufacturing, and more. Industrial process heating is typically energy and emissions intensive, compromising 30% of greenhouse gas emissions from the industrial sector [29]. Process heat equipment operates on a broad temperature range, from 150 to 1600°C [30]. Opportunities exist for NPPs to supply steam or heat to low- or high- temperature process heat applications.

Industrial electricity can take many forms: powering electronics, serving data centers, serving cryptocurrency mines, and more. Data centers in particular are predicted to proliferate significantly with the demand for artificial intelligence growing [31]. Data center developers and owner-operators are looking for carbon-free energy resources, some even considering behind-the-meter nuclear energy [32].

Compatibility between industrial loads with an N-R HES depends greatly on how critical the load is and if there are flexibility services offered. In some cases, the thermal or electric industrial load could be the primary load, with the grid and/or other end-use being the secondary, deferrable load to direct any amount of excess energy to. Or, if the industrial load is a flexible, it can serve as the deferrable or flexible load. Thermal or electrical energy storage could be used to supplement the flexibility of the system.

2.2.3.4 Microgrids and District Energy Systems

N-R HESs may be desired for powering interconnected loads that can be islanded from the main power grid. Examples of such systems include microgrids or district energy systems. A microgrid is a group of interconnected distributed generation resources and loads that can be operated in grid-connected and islanded mode. Microgrids have the potential to increase power quality, energy security, and efficiency [33, 34]. Research is emerging investigating the role of nuclear and N-R HESs in microgrid systems [35, 36].

District energy systems distribute heat, hot water, steam, or chilled water from a centralized source to nearby buildings. These systems are often used in colleges and universities, healthcare systems, and other industrial complexes [37]. The concept of bypassing steam around the turbine in an NPP to provide heat to a district energy system is under investigation. If successful, bypassing steam around the NPP turbine has potential to increase the thermal efficiency of the NPP and provide economic benefits [38].

2.2.4 Current State of Development of Nuclear-Renewable Hybrid Energy Systems

Full-scale operational N-R HESs have yet to be deployed, but research is ongoing to document their technical and economic feasibility. Current efforts mainly involve developing modeling and simulation tools for determining system feasibility. Modeling tools are also being developed to address technical integration challenges, and conceptual economic analyses are being used to identify methods for cost reduction and scalability opportunities [39] [40]. The U.S. Department of Energy (DOE) Office of Nuclear Energy maintains a program on Integrated Energy Systems (IES) to evaluate options for N-R HESs and coordinated use of nuclear and renewable energy to meet diverse energy needs [8].

N-R HES development can be informed by related efforts across the energy industry. For example, non-nuclear microgrids, another system that closely couples power resources and loads and may have similar control schemes, are already deployed commercially [41]. Progress is also being made in the understanding of how to couple nuclear resources with non-grid loads, which is needed in multi-end use N-R HESs. For example, nuclear-powered hydrogen demonstration projects are ongoing in the U.S., with hydrogen currently being produced at Nine Mile Point [42], and an additional demonstration project soon to follow at Prairie Island Nuclear Generating Plant [43]. Nuclear is also being considered for behind-the-meter electricity for emerging data centers [44, 45]. The Electric Power Research Institute's (EPRI) Nuclear Beyond Electricity focus area is investigating new opportunities for existing and future nuclear power plants to participate in markets beyond those solely supplying the electric power grid [46]. Synergistic efforts across these adjacent topic areas can inform methods for overcoming challenges for N-R HESs. As described in detail in the next section, a majority of research efforts for N-R HESs are currently focused on feasibility, modeling, and techno-economic studies.

2.3 Existing Literature on Selecting Optimal Hybrid Energy System Configuration

Much of of today's research efforts for N-R HESs include investigating their technical and economic feasibility, using various modeling and simulation tools to build and analyze different configurations of a hybrid system. These studies seek to determine if nuclear resources are capable of coupling with renewables to prevent either renewable curtailment or prevent times of insufficient power generation. Studies consider multiple generation resources serving one or multiple loads, and some isolate nuclear to serve multiple loads to investigate the question of nuclear flexibility or load following. The rest of this section provides a detailed overview of relevant literature the research proposed in this report builds from.

This research proposes a multi-criteria selection framework for N-R HES configurations to support holistic and rigorous decision-making when choosing optimal energy generation resources and end-use loads. The proposed framework provides a novel mechanism for identifying requirements, prioritizing relevant evaluation criteria, and comparing performance of energy generation and end-use options on these criteria. New contributions provided with the proposed selection technique include the following:

- A method for identifying exclusionary requirements, prioritizing and weighing relevant evaluation criteria, and comparing performance of energy generation and end-use options on these criteria.
- Demonstration of how to use the proposed technology selection framework.
- Techno-economic analysis of a case study system using the HOMER Pro and MATLAB-Simulink software tools.

Current literature analyzes hybrid systems with multiple different configurations and operational modes over various metrics. The work in [47] and [48] analyze technical and economic performance of N-R HESs in service to the grid only, determining the system's levelized cost of energy (LCOE) in optimization results. The work in [49, 50, 51, 52] consider optimizing various combinations of nuclear, renewables, and diesel generators to serve hydrogen production and power grid loads. Technical performance metrics in these studies include electric and thermal demand fulfillment and ability for the nuclear resource to load follow. Economic metrics include capital and operating costs, LCOE, net present value (NPV), internal rate of return (IRR), and payback period. The work in [53] attributes CO_2 emissions to various system configurations. Other research considers hybrid nuclear-renewable systems that serve microgrids [35, 54], desalination plants [10, 55], and district energy systems [56]. Metrics used to determine optimal design in these studies are similar to those discussed above: ability to meet required load demand, nuclear load following capability, LCOE, and NPV.

Despite the growing analysis of N-R HES technical feasibility and economic characteristics, there are fewer analyses that consider factors beyond economic performance. While costs are typically of high importance, the least expensive system may not be optimal if, depending on decision makers' priorities, it does not serve the desired business mission, does not achieve the highest CO_2 emission reductions, imparts higher environmental impact, or is unable to scale rapidly. Thus, this work seeks to describe a multi-criteria decision making framework for identifying an optimal N-R HES configuration based on a decision maker's specific priorities.

Various physics-based and data-based methods have been developed to support prediction and optimized decision making across a range of industries and applications (e.g., predicting stochastic process variables [57], predicting the condition of industrial infrastructure [58], grid integration of energy resources [59, 60], modeling flow applications [61], flood prediction [62], and the importance of accurately identifying process parameters [63]), where aspects of these approaches can be adapted to other decision making frameworks to enhance performance. Work does exist on multi-criteria decision making in other applications beyond N-R HESs, and to a limited degree specifically for N-R HES configuration selection. For example, studies exist that consider multi-criteria selection frameworks for hybrid renewable energy systems that do not include nuclear [64, 65, 53]. Outside of an energy context, investigators in [66] used multi-criteria selection for rainwater harvesting sites. While investigating systems serving distinctly different purposes, these studies emphasize how evaluating selections on multiple criteria can influence results compared to single-criterion results. Work in [67] describes a detailed framework for assessing advanced nuclear reactor designs, emphasizing the many assessment criteria that must be considered before a reactor design is selected for deployment. Research proposed in [68] uses an analytical hierarchy process to assess an N-R HES on three criteria: profitability, flexible operation, and safety. A multi-criteria decision making tool for selecting a N-R HES configuration in rural Nigeria that includes economic, technical, environmental, and social criteria, with performance metrics informed by HOMER Pro outputs is presented in [54].

Compared to the earlier work, the proposed approach is new in the following aspects:

- This research expands work on multi-criteria decision making methods specifically for hybrid energy systems that include nuclear energy resources.
- The proposed method considers both exclusionary requirements and preferred evaluation criteria relevant to N-R HESs. Considering requirements allows for initial screening to avoid detailed assessment of irrelevant options. Considering multiple evaluation criteria ensures robust, holistic decision making based on various stakeholder priorities.
- Along with a method for initial down-selection of technology options, this work analyzes proposed system performance with HOMER Pro and MATLAB-Simulink.

2.4 Chapter Summary

N-R HESs are being considered to optimize the benefits of each technology to efficiently decarbonize energy systems. These systems can take multiple forms but are often considered in the context of multiple generation technology types serving multiple end-uses. For example, with a mix of firm nuclear energy resources and variable renewable energy, the system can serve required loads like local power grids and divert energy to decarbonize non-critical loads like hydrogen production or desalination during times of excess energy, allowing for efficient decarbonization. Efforts are underway to develop methods for evaluating the feasibility of N-R HESs and developing frameworks for selecting optimal configurations. With much existing literature focusing on selecting configurations based on economic optimization, this work provides a multi-criteria selection framework that considers a variety of prioritized performance criteria.

CHAPTER 3: PROPOSED MULTI-CRITERIA TECHNOLOGY SELECTION FRAMEWORK FOR N-R HESs

3.1 Chapter Introduction

This chapter describes a multi-criteria technology selection framework for determining a preferred technology configuration for a nuclear-renewable hybrid energy system. The chapter begins by proposing a general structure for the selection framework, including details on selecting and prioritizing evaluation criteria and performing pairwise comparisons on performance characteristics across technology options. To inform case studies, this chapter also includes a preliminary, high-level assessment of select potential N-R HES end-use and generation technology options on example evaluation criteria.

3.2 Framework Structure

The proposed technology selection framework takes a multi-step approach, first by defining requirements for potential end-use loads and then stepping through a prioritization exercise to down-select remaining end-use options based on priority evaluation criteria. Once end-use loads are determined, a similar process follows for determining generation technologies: external requirements along with those imposed by the end-use screen out unsuitable generation technology options and a final "optimal" selection is based on performance on prioritized evaluation criteria. A summary of the selection framework process is shown visually in Fig. 3.1.

Example options for generation resource and end-use technology combinations for a N-R HES are described in Sections 2.2.3 and 2.2.3 are listed in Table 3.1 for reference. A specific combination of generation resource types serving specific end-use types

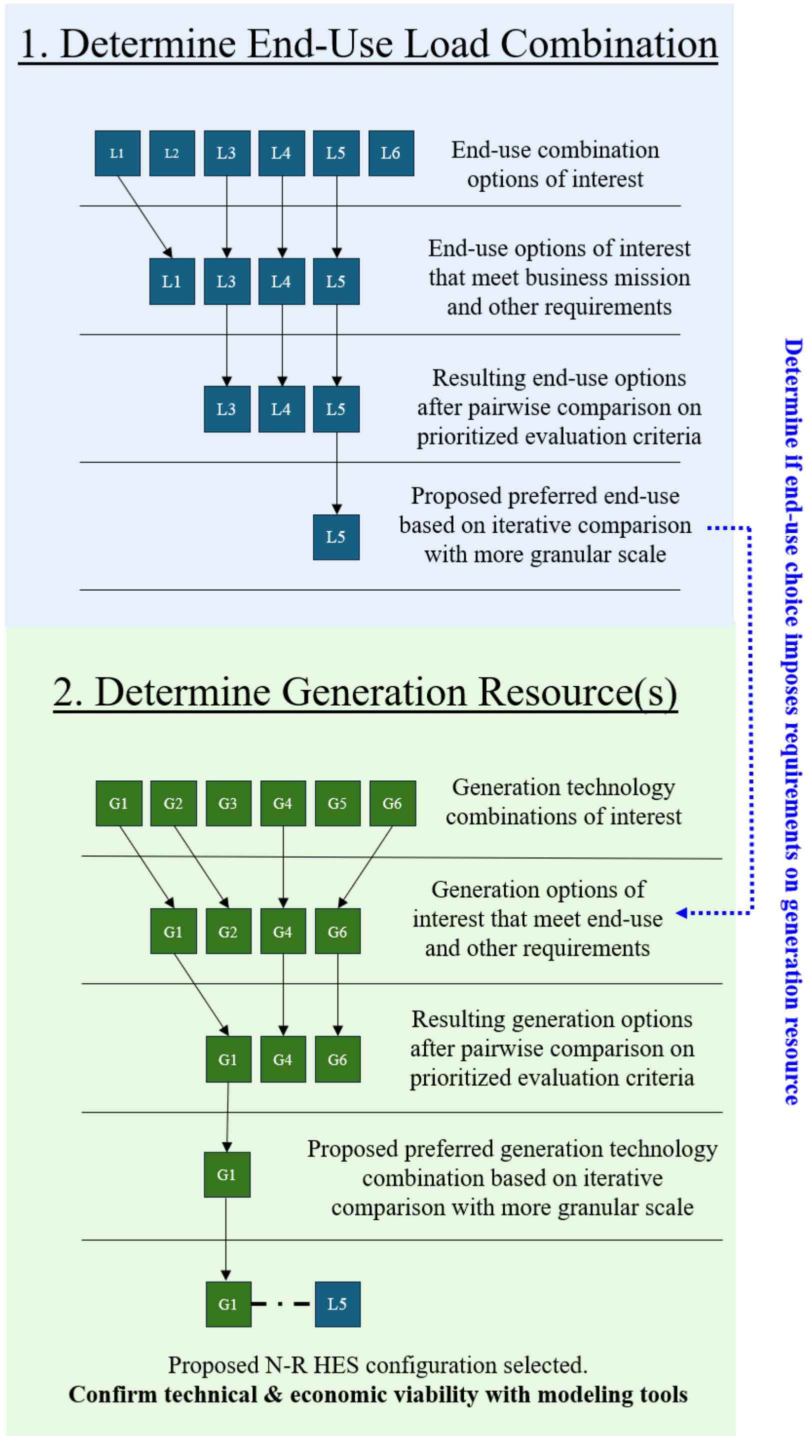


Figure 3.1: Visual overview of proposed N-R HES multi-criteria technology selection framework. L1-5 are generic end-use load combinations under consideration. G1-5 are generic generation resource technology combinations under consideration.

constitutes an N-R HES configuration. Extensive assessment of technology subclasses and manufacturer-specific technology designs are outside the scope of this work, but a similar framework could be applied for design-level selection.

Table 3.1: Example Generation Resource and end-use load combinations for an N-R HES

Example Generation Resource Combinations
Nuclear + Solar PV
Nuclear + Wind
Nuclear + Solar PV + Wind
Any of the above options + Diesel Backup
Any of the above options + Battery Storage or Thermal Energy Storage
Example Energy End-Use Load Combinations
Grid Electricity
Grid Electricity + Hydrogen Production (Electricity or Thermal Energy)
Grid Electricity + Desalination (Electricity or Thermal Energy)
Grid Electricity + Industrial Electricity and/or Process Heating
Microgrid Electricity
District Heating
Combination of any of the above end-uses

Two key definitions are first presented [67]:

- **Requirements**: Exclusionary metrics a technology must meet. Compliance on requirements is necessary, and technologies that do not meet the requirements are excluded from further analysis. Requirements are exclusionary factors.

- **Evaluation Criteria**: Technical and business considerations different technologies will be evaluated against. Evaluation criteria provide the categories upon which different technology options will be compared against each other. Unlike requirements, a technology may perform poorly on one or more criteria but may not necessarily be excluded from further evaluation (e.g., if those criteria are low priority). Each evaluation criteria should have clearly defined and measurable metrics to examine each technology option.

Technologies of interest undergo a “first screening" to eliminate options that will not meet requirements. Technologies are then further down-selected based on performance on multiple, prioritized, evaluation criteria. The proposed selection framework follows the steps described in Algorithm 1 and Algorithm 2.

Algorithm 1 Algorithm to Determine End Use Combination

1: Define business mission and other requirements (exclusionary factors).
2: Identify end-use technologies of interest and screen out technologies that do not meet requirements.
3: Define evaluation (preference) criteria.
4: Prioritize evaluation criteria and determine weighting factors by a pairwise prioritization matrix. For each criteria, rate each criteria as 4, 2, 1, 0.5, or 0.25 if it is much more, more, as, less, or much less important, respectively, than the other criteria. Sum pairwise ratings across all criteria to determine overall weights. [For example, Table 3.2a shows that Evaluation Criteria 1 is more important than Criteria 2, and much more important than the n^{th} criteria. Criteria 2 was deemed less important than the n^{th} criteria.] Determining priorities and weighting factors is an iterative process among stakeholders and decision makers.
5: Compare remaining end-use options via pairwise comparison matrices. For each option, set a baseline option. Rate the other options as 1, -1, or 0 if they perform better, worse, or the same, respectively, on each evaluation criteria. [Table 3.2b shows an example where Option 2 performs better compared to Option 1 on Criteria 1 and worse on Criteria 2.] Note that because this process will be repeated with other options as the baseline, ratings with magnitudes not equal to one or zero are not needed. Apply criteria weights, sum rating across criteria, and normalize. Create a new comparison matrix and repeat process with next option set as baseline until each option has been used as a baseline. Sum normalized results for each option for each comparison matrix. Options with the highest final rating are the "optimal" choice.
6: If there is no one clear winner after Step 5, repeat pairwise comparison with highly ranked options with a more granular rating scale (e.g., rate options on criteria with a 1-5 scale vs a -1, 0, or 1 scale).

A proposed preferred end-use combination for the N-R HES is selected after all the steps in Algorithm 1 are complete. This end-use imposes some requirements for the generation resource, such as technical compatibility, form of energy needed (electric vs. thermal), required energy output to meet demand, or location requirements. These imposed requirements feed directly into Algorithm 2, which determines the generation resource combination. Algorithm 2 follows a similar process to Algorithm 1.

After Algorithm 2 is complete, a proposed preferred generation resource combina-

Table 3.2: (a) Example Criteria Prioritization Matrix and (b) Example Pairwise Comparison Matrix

(a) Example Criteria Prioritization Matrix

	Evaluation Criteria 1	Evaluation Criteria 2	···	Evaluation Criteria n
Evaluation Criteria 1	1	0.5	···	0.25
Evaluation Criteria 2	2	1	···	2
⋮	⋮	⋮	···	⋮
Evaluation Criteria n	4	0.5	···	1

(b) Example Unweighted Pairwise Comparison Matrix

	Option 1 (baseline)	Option 2	···	Option n
Evaluation Criteria 1	0	1	···	0
Evaluation Criteria 2	0	-1	···	1
⋮	⋮	⋮	···	⋮
Evaluation Criteria n	0	1	···	-1

tion is selected to serve the proposed preferred end-use load(s). Thus, a potentially optimal full N-R HES configuration is determined based on both requirements and a set of prioritized evaluation criteria. Detailed modeling with software tools can commence for further technical and economic feasibility review. This process can be adapted to include any number of generation or end-use combination options, requirements, or evaluation criteria beyond those considered in this report.

3.3 Example Requirements and Criteria

While the proposed technology selection framework is generic and able to include any number of requirements, evaluation criteria, and system components, this report defines select evaluation criteria to inform an example evaluation. It is understood that a requirement for one organization may only be an optional criteria

Algorithm 2 Algorithm to Determine Generation Resource Combination

1: Examine requirements imposed by end-use selection and define other requirements for the generation resource option(s).
2: Identify generation technology combinations of interest and screen out technology options that do not meet requirements.
3: Define evaluation (preference) criteria.
4: Prioritize evaluation criteria and determine weighting factors via a similar pair-wise process described in Algorithm 1 Step 4.
5: Perform a pairwise comparison between remaining technology options based on evaluation criteria via a similar process described in Algorithm 1 Step 5.
6: If there is no one clear winner after the previous step, repeat pairwise comparison with highly ranked options with a more granular rating scale (e.g., rate options on criteria with a 1-5 scale vs a -1, 0, or 1 scale). This step should down-select to a single "preferred" option.

for another organization and vice versa. Organizations and stakeholders will need to define for themselves which metrics are exclusionary requirements and which are non-exclusionary criteria.

Example requirements or evaluation criteria include:

- **Alignment with Business Mission:** Future N-R HES adopters typically have made pre-determined business decisions to inform the purpose of deploying the system. This could be determined by market analyses and customer desires. For example, a utility may be interested in providing resources for a new market of industrial electricity customers demanding hourly matched carbon-free energy (24/7 CFE), helping pre-select the desired end-use options. Other considerations for business mission include desired budgets and deployment timelines.

- **Ability to Serve Load:** An N-R HES may be required to satisfy a primary load (a local grid load in many cases), and then divert excess energy to a secondary or deferrable load (a non-grid load in many cases). Once end-use loads are determined, understanding the required MW output of the generation resources, and to what extent a load can be deferred, informs what technologies are included in an N-R HES and allowed operational flexibility.

- **Location:** Adopters of N-R HESs will typically have a general location in mind for where it will be sited. For example, a utility may require the N-R HES be sited within its operating territory, or it may be deployed to meet a specific energy need in a specific location. The location of deployment may determine resource availability, and thus influence both end-use and generation options. For example, desalination plants would typically only be found in coastal areas. N-R HESs deployed in regions of exceptionally low solar resources (like far north areas), may be infeasible to include solar PV.

- **Capital Costs:** Fixed, one time, expense of acquiring and/or constructing a physical asset. Includes cost of land, cost of equipment/components/system infrastructure, cost of construction, project management and licensing costs. Measured in United States dollars (USD) or USD per kW of rated capacity. Note that this definition of capital cost includes overnight construction costs (expenses incurred from equipment, materials, and labor if the full system was built "overnight") plus owners costs (land costs, commissioning costs, inventory capital, etc.). Allowance for funds during construction (interest expenses accumulated during plant construction) is also considered when determining total capital required to implement infrastructure.

- **Operations and Maintenance Costs (O&M):** Costs associated with regular, day-to-day, and year-on-year operation and maintenance of a physical asset. O&M considers costs associated with paying staff to operate and maintain assets, required resource costs, additional repair costs, material/component replacement costs. Certain O&M costs may be fixed, or independent of the number of operating hours a system operates for and is often expressed as USD per kW or per MW per year. Fixed O&M costs typically are due to routine operating and maintenance labor, maintenance material services, and overhead like administrative and general expenses. Other O&M costs are variable, and are based on the amount of power produced, and are expressed as USD per MWh produced. Variable O&M are often related to production-dependent consumables (e.g., water) or waste discharge costs. Fuel costs are often reported separately [69].

- **Carbon Emissions:** Amount of CO_2 emitted by a process per unit of production. Measured in units of CO_2 per kWh or unit product produced. Note that since emissions typically depend on the choice of generation resource, end-use options in isolation would score similarly on this metric.

- **Land Use:** Amount of land space needed for a resource, including the size of the physical asset, plus any additional land needed for the overall site (parking lot, offices, switchyards), other construction, and any additional buffer land needed between asset and next property/other infrastructure. Often measured in square meter, square feet, acre, or hectare needed on a total or per unit power basis.

- **Environmental Impact Potential:** A measure of how implementing a system or technology impacts the local surrounding environment and ecology beyond simply measuring carbon emissions. This metric is typically considered on a system life cycle scale, meaning environmental impacts should not only be considered during operation, but also impacts incurred during material and component sourcing, system construction, end of life, and decommissioning, including assessment of disposal of used materials or components.

  Environmental impacts can be measured across many different metrics, and entire fields of study exist for environmental life cycle analyses. Some common metrics relevant to N-R HES include [70]:

  – Air and water pollutant rates during N-R HES operation (for example, if an industrial end-use produces non-CO_2 pollutants), during upstream materials or component manufacturing, or during decommissioning and disposal at the end of the system's life.

- Amount of vegetation, natural land, and/or habitat area disturbed to implement and operate the system.
- Decibels of noise pollution induced by implementing the system. Noise pollution can be caused by sound emanating from moving parts within each N-R HES component, such as the spinning of blades from turbines used in an NPP, a diesel generator, or wind turbine. Solar PV inverters can also create noise.
- Amount of water use in constructing and operating the system. For example, NPPs require cooling water throughout their operational lifetime.
- Impacts due to toxicity of material used in system. For example, certain AR concept developers are considering using fluoride/lithium beryllium (FLiBe) molten salt for heat transfer capabilities [71]. Careful consideration of handling and disposal procedures will be needed as beryllium is a toxic element.
- Total solid waste when decommissioned.

• **Energy Justice Impacts:** Energy justice can be defined as "the goal of achieving equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those disproportionately harmed by the energy system [72]." Careful consideration of disproportionate impacts of energy infrastructure planning can mitigate further harm to already burdened communities. Global efforts towards energy justice are increasing as communities seek a just energy transition. Energy justice impacts can be measured across multiple groups, including energy or electricity customers, local communities, workers, and society. Specific metrics include energy affordability, procedural justice, economic participation and community ownership, and health and environmental impacts [73]. Fully understanding energy justice impacts requires detailed, geographically-specific analysis.

- **Technology Maturity:** Also known as technology readiness level (TRL), technology maturity is a measure of where a technology is in its development, from basic research to "flight proven" and widely commercially procurable. It also includes measures of how easy a technology is to deploy, measuring maturity of supply chain and availability of suppliers. TRL is typically defined on a scale of 1-9 [74], [75], [76]. In addition to the 1-9 TRL scale, this analysis presents insights on how widely deployed a technology is, indicating a measure of extent of deployment (market uptake).

3.4 Performance of Energy End-Use Load Options on Select Evaluation Criteria

The multi-criteria technology selection framework described in Section 3.2 provides a mechanism for rigorous comparison between options for N-R HES configuration. While detailed analysis should be undertaken to analyze comparative ratings on each evaluation criteria when proceeding through the proposed framework, it is useful to have a high-level reference of example technology option performance on certain evaluation metrics while using the comparison framework.

This section will provide a preliminary, high-level assessment of select potential energy end-uses in an N-R HES against a subset of the evaluation criteria identified in Section 3.3. This section is limited to criteria with more explicit, quantitative performance metrics that can be determined via literature review: capital costs, O&M costs, carbon emissions, land use, technology maturity, and extent of deployment if technology is mature. Per a user's discretion, other requirements and criteria described in Section 3.3 or additional criteria not listed can be considered when using the selection framework methodology.

Example technology approaches (e.g., PEM electrolysis, RO desalination, chemical manufacturing) were chosen for examination based on compatibility with nuclear energy and availability of performance data and should not be taken as an endorsement of a technology approach. To the extent possible, comparison is done on a per unit power or energy capacity basis as a system may not necessarily be sized at this stage of technology selection. Performance metrics were gathered from literature review. All cost metrics were adjusted to 2024 USD. Due to limited deployment or analysis of certain technologies, actual costs or performance may be different between values gathered via literature below and what might actually be incurred if a N-R HES is actually deployed today. Because transmission required is highly dependent on system size and complexity, costs of transmission and power distribution are not represented in this analysis for every technology. Cost and performance metrics presented are not specific to any one technology vendor's design. Cost of power supplied for use in these end-us applications is not detailed as that is dependent on generation resource selection and will be explored in Section 3.5.

While microgrids or district/industrial heating applications may be exceptions, it is assumed that grid electricity will often be a required energy end use, and that non-grid end-uses would be implemented in addition to supplying the grid. Thus, for simplicity, the analysis in this section proceeds with analyzing non-grid end uses in isolation. In other words, the cost of grid infrastructure and loads are not included in the analyzed cost of an electrolyzer or desalination plant, as it is assumed that the cost of serving a grid load would not deter a system planner from supplying power to the load. Additionally, it can be assumed that that the grid loads the N-R HES will provide electricity to (e.g., existing residential or commercial buildings) are already constructed and operating and that minimal to no additional expenditures are required to serve said grid load.

A high-level analysis of of select potential energy end-uses (excluding the assumed required electric power grid end-use) in an N-R HES against select evaluation criteria is as follows. Assumptions are noted when appropriate.

- **PEM Electrolyzer**
  - **Capital Costs:** $2,230/kW (2024 USD), based on 2024 analysis of PEM electrolyzers in [77] derived from ongoing work within the H2NEW Consortium.
  - **O&M Costs:** $111/kW-yr (2024 USD), assuming fixed operating costs are 5% of the total installed capital costs, per the U.S. DOE [77].
  - **Carbon Emissions:** None in addition to those associated with energy generation option.
  - **Land Use Requirements:** Land area needed for process and ancillary equipment is approximately 0.43 acres/MW, based on analysis of an alkaline electrolyzer system, which can be taken to be reasonably representative of land requirements of other electrolyzer technologies like PEM electrolysis. Approximately 1 acre/MW is needed if roads and utility corridors are included. [78].
  - **Technology Maturity:** 9. PEM electrolyzer technology is commercially mature and deployed in various locations [79].
  - **Extent of Deployment** (if commercially mature): Proof of market stability of PEM electrolyzers has yet to be reached [79]. Large scale PEM electrolyzers (capable of producing tens of thousands of kg of H_2 per day) have yet to be deployed [77].
- **RO Desalination**

- **Capital Costs:** $2,500-$18,000/kW, per capital expenditure estimates reported in [80, 81, 82], and assuming conservatively that RO desalination has an energy intensity of 4 kWh. Note that sea water RO desalination is cited as more expensive and more energy intensive than brackish water desalination [83, 81].
- **O&M Costs:** $440-$3,200/kW, assuming non-energy operating costs account for approximately 34% of total costs, and capital expenditures accounts for approximately 52% of total costs [83, 82].
- **Carbon Emissions:** None in addition to those associated with energy generation option.
- **Land Use Requirements:** On the order of .5 acres/MW, including support infrastructure [84]. Additional land may be needed for roads and utility connection.
- **Technology Maturity:** 9. RO desalination technology has been commercially mature for decades.
- **Extent of Deployment** (if commercially mature): RO desalination has reached market stability with widespread deployment in areas such as the Middle East. As of 2020, of the approximately 16,876 operational desalination plants, RO desalination accounted for 85% [83].

- **Data Center (Large)**
  - **Capital Costs:** $11,000-$16,000/kW (2024 USD), although capital costs are highly dependent on data center type, size, and location [85, 86].
  - **O&M Costs:** $300-$1,200/kW per year [85]
  - **Carbon Emissions:** None in addition to those associated with energy generation option.

- **Land Use Requirements:** Minimum 40 acres, with more potentially needed for larger data centers [87]. High density data centers can consume 10-150 kW per square foot [88].
- **Technology Maturity:** 9. Data center technology is fully mature and used widely.
- **Extent of Deployment** (if commercially mature): Data centers have reached market stability and extensive deployment to serve a computation-reliant society. Trends in data center deployment and data center size are set to increase with strong demand for AI technology and associated computational demand [31].

- **Industrial Process Heating – Chemical Manufacturing Facility**
  - Note that in many cases, because industrial heating needs are ubiquitous, a group considering a N-R HES may have industrial process heating in mind as its sole business mission, allowing a use to use the proposed framework simply for the generation technology options. Also, in many cases, industrial processes require high reliability, and thus an N-R HES serving industrial processes may not serve additional loads. Regardless, initial performance characteristics for a chemical manufacturing facility are given below as an example.
  - **Capital Costs:** Highly dependent on process choice and size of industrial facility. Some of the most expensive chemical plant construction costs were on the order of ones to tens of billions of dollars [89]. Since chemical manufacturing facilities have various types and levels of complexity not necessarily directly proportional to energy input capacity, costs are not presented on a dollar per kW basis.
  - **O&M Costs:** A survey conducted in 1967 among plant engineering mem-

bers of the American Institute of Plant Engineers found that operating costs for chemical plants were one half of the capital plus installed cost or equipment [90]. 2024 O&M costs for chemical manufacturing facilities are likely different than what was observed in 1969, but this study indicates O&M costs do comprise a large amount of total costs.

  - **Carbon Emissions:** Generally, in most cases except nitrogen-based fertilizer production, none in addition to those associated with energy generation option. Nitrogen-based fertilizer production typically uses natural gas as a product, resulting in carbon dioxide as a byproduct. Additionally, depending on the process, chemical manufacturing facilities may emit other pollutants.
  - **Land Use Requirements:** Land use will be driven by the type and size of the process heating/manufacturing facility needing to be served. In some cases, since industrial heating is a mature, ubiquitous process, an N-R HES may target serving an existing process heating facility, reducing the need to disturb land specifically for the end-use. In this case, newly disturbed land area would be primarily driven by generation technology choice.
  - **Technology Maturity:** 9.
  - **Extent of Deployment** (if commercially mature): Industrial process heat for chemical manufacturing is used commercially across the globe.

- **Microgrid Electricity**
  - Here impacts of implementing a microgrid system on already existing loads are analyzed. It is assumed that the microgrid loads (residences, commercial facilities) are already constructed and the cost to build and operating the loads themselves will not add additional expenditure.

- **Capital Costs:** \$530-\$2,700/kW for controls, soft costs, and additional infrastructure (non-generation/non-storage expenses), per NREL analysis. This wide range encompasses analysis of component-level breakdowns of costs of microgrids with four levels of increasing complexity, where complexity is based on "number of DER assets, amount of renewable energy relative capacity, energy storage, control architecture, and enterprise-level capabilities [91]."
- **O&M Costs:** Highly dependent on system size and complexity. A large driver of O&M costs for a microgrid will be the choice in energy generation technology included.
- **Carbon Emissions:** None in addition to those associated with energy generation option.
- **Land Use Requirements:** Since it is assumed power loads are already constructed, newly disturbed land use will be primarily driven by generation technology costs.
- **Technology Maturity:** 9, microgrids are commercially mature and have been deployed in various settings [34, 92].
- **Extent of Deployment** (if commercially mature): Despite proof of commercial operation and recent growth, they have yet to be widely deployed. For example, microgrids provide less than 0.3% of U.S. electricity [92].

- **District Heating**
  - **Capital Costs:** Non-generation capital costs will primarily be driven by costs of piping for heat energy distribution, heat pump substations to generate temperatures suitable for use, and system installation. Analysis in [93] estimate system-wide network piping and installation costs to be \$200-600/meter depending on pipe diameter, fluid pump CAPEX to be

$40/m^3/hr, and total installed cost of the heat pump substation to be $780/kW (thermal). Users may incur further costs from pipes installed on the user side (for example, piping inside housing or buildings to properly distribute heat). Since the capital costs of a district heating system are highly dependent on the physical area of the system, there is no attempt here to convert cost components to $/kW values like in other technology cases.

– **O&M Costs:** Fixed O&M for a district heating system, excluding the heat plant, is estimated to be $4,000/MW/year, primarily driven by the substation O&M. Variable O&M are suggested to be $2.41/MWh [93].

– **Carbon Emissions:** None in addition to those associated with energy generation option.

– **Land Use Requirements:** Land use will primarily be driven by area of buildings and facilities needing to be served and generation technology option. Pipes (energy distribution infrastructure of the district energy system) may be placed underground or inside buildings, reducing amount of additional land needed to be permanently disturbed.

– **Technology Maturity:** 9, district heating has been demonstrated commercially in campuses (universities, hospitals, etc).

– **Extent of Deployment** (if commercially mature): While district energy using fossil (diesel, natural gas) generation in many systems globally, district energy systems coupled with nuclear energy/heat have yet to be demonstrated.

It is possible to consider any combination of the above energy end-uses in the N-R HES system. For example, an organization considering an N-R HES may want to consider performance of a system that serves the power grid, a hydrogen production facility, and a desalination plant simultaneously. Costs and performance of systems with three or more end-uses are highly dependent on individual end-use size and technology option and are thus not included in this high-level analysis.

3.5 Performance of Energy Generation Options on Select Evaluation Criteria

Once energy end-uses are selected, some requirements for energy generation options in an N-R HES may become apparent. For example, the end-uses selected determine whether or not the generation technologies will need to supply only electricity, only thermal energy, or need a mix of both energy forms. The form of energy needed informs operational modes and infrastructure needed for the nuclear asset and guides decisions on types of energy storage that may be considered. Also, when end-uses are determined, a system planner may be able to understand the size of the required load, informing the size of energy generation required. If the system is to be deployed in a location where a generation type may not be able to produce sufficient energy (e.g., solar PV in far north geography), that technology may be able to be eliminated before pairwise comparison.

Because this section does not make assumptions about a decision maker's preferred end-use or other requirements for the N-R HES, this analysis proceeds similarly as in Section 3.4 to provide a preliminary, high-level assessment of select potential energy generation options in an N-R HES against a subset of the evaluation criteria identified in Section 3.3. Cost metrics are presented in 2024 USD. Results detailed are based off those represented in literature and, due to inherent uncertainty, may not be the actual costs incurred if an N-R HES is built. As in the previous section, cost and performance metrics given below are not representative of a specific technology developer's design.

- **Nuclear SMR**
  - **Capital Costs:** $8,780-11,500/kW [94]
  - **O&M Costs:** $189-271/kW-yr fixed and $10-12/MWh variable non-fuel

O&M costs. Fuel costs of $0.77/MMBtu [94].

- **Carbon Emissions:** None
- **Land Use Requirements:** 50-500 acres per reactor if a new reactor is being sited near an existing nuclear site. If not, and a cooling water reservoir is needed, an additional 4,000 acres may be needed [67].
- **Technology Maturity:** 7-8. SMR demonstration facilities are being constructed and designs approved (examples include [95, 96]) but the technology has yet to reach commercial maturity [97].
- **Extent of Deployment** (if commercially mature): While SMRs have not reached commercial operation stage, many demonstration projects are ongoing and planned across the globe [97].

- **Solar PV**
  - **Capital Costs:** $1,460-1,660/kW [94]
  - **O&M Costs:** $16-20/kW-yr fixed [94]
  - **Carbon Emissions:** None.
  - **Land Use Requirements:** 5-10 acres/MW [98]
  - **Technology Maturity:** 9, solar PV technology is commercially mature.
  - **Extent of Deployment** (if commercially mature): Widely deployed with adoption rapidly increasing in recent years.

- **Onshore Wind Energy**
  - **Capital Costs:** $1,650-1,950/kW [94].
  - **O&M Costs:** $39-57/kW-yr fixed [94].
  - **Carbon Emissions:** None.

  - **Land Use Requirements:** 30-140 acres/MW needed for total project area, although only about 1-4 acres/MW are directly impacted [99].
  - **Technology Maturity:** 9, wind energy technology is commercially mature and deployed in many locations.
  - **Extent of Deployment** (if commercially mature): Widely deployed with adoption rapidly increasing in recent years.

- **Diesel Generator Backup**
  - **Capital Costs:** $1,560/kW [100]. Note that it is assumed for most cases, diesel generator is used as a backup, meaning nuclear and renewable resources would be sized to meet load size independent of DG capacity. In this case, including diesel in the system would always add cost.
  - **O&M Costs:** $0.07-0.74/kWh variable non-fuel O&M costs, depending on type and size of generator under consideration [101]. As explained above, assuming DG is built as a true backup that does not impact nuclear or renewable capacity, including the technology will always increase total O&M costs. As of the end of July 2024, diesel fuel prices in the U.S. were $3.77 per gallon, or $27.4/MMBtu [102].
  - **Carbon Emissions:** 10,180 grams of CO_2 is released per gallon of diesel fuel consumed [20].
  - **Land Use Requirements:** On the order of 0.0034 acres/MW, per dimensions given for a representative 2 MW diesel generator set in [103].
  - **Technology Maturity:** 9, diesel generators are commercially mature and are widely deployed.
  - **Extent of Deployment** (if commercially mature): Widely deployed as backup power solutions and as primary power solutions in remote locations.

- **Battery Storage**
  - **Capital Costs:** $1,450-1,620/kW [94]
  - **O&M Costs:** $44-47/kW-yr [94]
  - **Carbon Emissions:** None in addition to those associated with energy generation option that would be used to charge batteries.
  - **Land Use Requirements:** 0.005 acres/MWh [104]. Note the per MW land use will be dependent on battery discharge time.
  - **Technology Maturity:** 9, battery storage technologies like lithium ion batteries have reached commercial maturity.
  - **Extent of Deployment** (if commercially mature): Battery storage deployments are increasing but are still in the "market uptake" stage, particularly for large scale projects [79].
- **Molten Salt Thermal Energy Storage**
  - **Capital Costs:** In terms of dollar per unit energy, [105] found the CAPEX for a 750 MWh capacity two-tank molten salt TES was $36.70/kWh.
  - **O&M Costs:** When considering costs per unit energy, [105] found representative O&M costs to be $7.7 per kWh per year.
  - **Carbon Emissions:** None in addition to those associated with energy generation option that would be used to input energy to the storage system.
  - **Land Use Requirements:** On the order of .004 acres/MW capacity for a two-tank molten salt thermal energy storage system, excluding additional land surrounding the tanks [106, 107].
  - **Technology Maturity:** 9, molten salt storage systems are currently deployed in concentrated solar power (CSP) plants [108].

– **Extent of Deployment** (if commercially mature): While widespread in CSP applications, molten salt thermal energy storage has yet to be widely used with direct coupling with nuclear energy.

As with the energy end-use options, a group considering an N-R HES may consider a variety of combinations of renewable, diesel, or storage technologies in addition to nuclear energy. Some may even consider a system where a suite of all technologies mentioned above are included as an option. When considering technology configurations that include multiple different non-nuclear assets, size of each component (e.g., kWs of capacity of wind or solar in a system that contains both resources) will be a driving factor of total costs and land impact. Iterative analysis can be done to optimize system size configurations. However, the proposed framework can use high-level, per unit power or energy assessments to quickly eliminate options.

The analysis above largely did not consider technologies needed to integrate multiple generation resources and end use loads, which can also influence capital and operational costs. For example, solar PV produces direct current (DC) electricity, requiring an inverter to convert DC into alternating current (AC) electricity. Alternatively, if a load requires DC, a rectifier may be needed to convert AC to DC. Significant inverter or rectifier capacity may be needed if there is significant solar resources in the N-R HES or if there is a load requiring substantial DC input. Additionally, sensing, communications, and control systems may need to be expanded in these tightly coupled systems to best coordinate resources. For systems delivering heat to end-use applications, suitable mechanisms for efficiently diverting heat from the nuclear plant must be applied, along with piping networks and heat exchangers. Costs due to additional transmission needs for electrical energy was also not considered in the analysis above. As stakeholder groups align on preferred N-R HES configuration across a variety of evaluation criteria, further assessment of integration technology needs can assist in refining project costs.

There are numerous potential evaluation criteria not detailed in this report, which here were limited to those with specific quantitative metrics readily available in open literature. For example, [109] presents a reference card of generation technologies across additional criteria an organization might consider when determining N-R HES configurations such as ease of permitting and water use intensity. Additionally, this section did not explore geographical influences on cost and performance metrics. Before final decisions are made, stakeholders should ensure rigorous and site specific performance assessments are completed to fully understand project costs and impacts.

3.6 Chapter Summary

This chapter provided an overview of the proposed multi-criteria selection methodology for determining technology choices in an N-R HES. This framework has users identify requirements for technology resources, select and prioritize evaluation criteria, compare technology options in a pairwise manner, and evaluate optimal technologies based on weighted performance scores. End-use technologies should be determined first to inform requirements for generation resource technologies. Descriptions of example performance criteria were given, and high-level evaluation of select technologies was provided. Although this chapter only presented information on a select number of evaluation criteria and only assessed a select number of technology options, it provided a starting point for N-R HES configuration analysis. Built with flexibility in mind, the technology selection framework proposed can be used to compare any number of technology options across any number of evaluation criteria.

CHAPTER 4: FRAMEWORK DEMONSTRATION AND CASE STUDY DOWN-SELECTION

4.1 Chapter Introduction

In this chapter, two case studies are presented to demonstrate the usefulness of the technology selection framework. This demonstration begins with a simple case study with limited technology options compared across limited evaluation criteria. Then, the second case study steps through the framework process with a more complex scenario. The two presented prompts showcase how decision maker priorities directly influences N-R HES configuration choice.

4.2 Selection Framework Methodology Demonstration

In this section, two case study prompts are used to inform the selection framework methodology demonstration. These case studies begin with a simple example, then progress to a more complicated example in the second case study. While both case study prompts are aligned with general perspectives a group interested in decarbonization may have, both case study prompts and assumed business missions, requirements, and priorities of example decision makers are not representative of a specific organization's perspective.

4.2.1 Case Study 1 Down-selection

In this initial, simple case study, the selection framework is demonstrated through the following prompt:

A North Carolina (NC) utility has a business mission to service either a data center or a large, 100 MW electrolytic hydrogen production facility alongside a local community power grid load. They seek to deploy a nuclear-renewable hybrid system

Table 4.1: Case Study 1 Criteria Prioritization Matrix

	Capital Costs	Carbon Emissions	Technology Maturity
Capital Costs	1	0.5	0.5
Carbon Emissions	2	1	0.5
Technology Maturity	2	2	1
Sum	5	3.5	2
Normalized Sum	0.48	0.33	0.19

to serve these loads. They require that all energy demand of the community load must be met at all hours. They determine that low capital costs and low carbon emissions are more important than other metrics. However, low capital costs are more important than carbon emissions. They are also considering technology maturity and extent of global technology deployment in their evaluation as an indicator for how ready the technology is for immediate deployment.

Following the framework steps, down-selection begins with determining the business mission and requirements for the end-use. The business mission is to serve the grid alongside a data center or an electrolytic hydrogen production facility. The data center or electrolyzer must be able to operate in NC. These requirements immediately down-selects options to two candidate end-use combinations: 1) grid electricity + electrolytic hydrogen production and 2) grid electricity + industrial electricity for a data center. The evaluation criteria are capital costs, carbon emissions, and technology maturity & extent of deployment.

The above criteria are then prioritized to determine weighting factors (Table 4.1). The resulting weighting factors for Capital Costs, Carbon Emissions, and Technology Maturity are 0.48, 0.33, and 0.19, respectively. A pairwise comparison of the two end-use options is performed based on the prioritization criteria. Table 4.2a shows the pairwise comparison matrix. Table 4.2b shows the results with weights applied to each criteria and results summed across criteria. Since $0.29 > 0$, the Grid +

Electrolytic Hydrogen Production end-use option is the priority choice.

Table 4.2: (a) Unweighted Case Study 1 End-Use Pairwise Comparison Matrix,, and (b), Weighted Case Study 1 End-Use Pairwise Comparison Matrix

(a) Case Study 1 End-Use Pairwise Comparison Matrix, unweighted

	Grid + Data Center	Grid + Electrolytic Hydrogen Production
Capital Costs	0	1
Carbon Emissions	0	0
Technology Maturity	0	-1

(b) Case Study 1 End-Use Pairwise Comparison Matrix, weighted

	Grid + Data Center	Grid + Electrolytic Hydrogen Production
Capital Costs	0	0.48
Carbon Emissions	0	0
Technology Maturity	0	-0.19
Sum	0	0.29

The generation side of the N-R HES must now be selected. The first requirement, imposed by the end-use selection, is that the generation resource combination must provide the correct form of energy. In this case, only electricity will be delivered to the end-uses and no thermal energy will be used. The second requirement is that the generation resource must serve the required load, meaning it must be sized appropriately to reliably serve the local grid load. The electrolyzer is not required to run at full capacity and constantly receives 100 MW of electricity. In other words, the electrolyzer may be treated as a secondary variable load to utilize excess energy when grid loads are satisfied. For this simple example, a community grid load with peak demand comparable to the size of the nuclear resource is considered. During times when the electricity supply exceeds the local community grid demand, excess power will be delivered to the electrolyzer. There is also a requirement that this system be sited in North Carolina. Given suitable solar resources throughout the state, this locational requirement does not disqualify solar energy. Wind resources are relatively lower in North Carolina compared to other states, so wind energy is excluded.

Thus, the following generation technology combinations will be considered:

1. Nuclear + Solar PV (N+PV)

2. Nuclear + Solar PV + Diesel Generator Backup (N+PV+DG). Note that nuclear and PV would still be sized to serve most of the load in this configuration.

3. Nuclear + Solar PV+ Battery Energy Storage (N+PV+B)

For this example, the nuclear resource is taken to be a single, 80 MW small modular reactor. Solar resources are sized at 20 MW capacity, and electrolyzer capacity is 100 MW. It is assumed that capital costs for the system will scale with a greater number of generation technologies included. Evaluation criteria priority and weights remain the same as in the end-use selection. Pairwise comparison on evaluation criteria is then performed (Table 4.3a, Table 4.3b, Table 4.3c).

Table 4.3: Unweighted case Study 1 Pairwise Comparison Matrices: (a) N+PV Baseline, (b) N+PV+DG Baseline, and (c) N+PV+B Baseline

(a) Case Study 1 Pairwise Comparison Matrix (N+PV Baseline), unweighted

	N+PV (baseline)	N+PV+DG	N+PV+B
Capital Costs	0	-1	-1
Carbon Emissions	0	-1	0
Technology Maturity	0	0	-1

(b) Case Study 1 Pairwise Comparison Matrix (N+PV+DG Baseline), unweighted

	N+PV	N+PV+DG (baseline)	N+PV+B
Capital Costs	1	0	0
Carbon Emissions	1	0	1
Technology Maturity	0	0	-1

(c) Case Study 1 Pairwise Comparison Matrix (N+PV+B Baseline), unweighted

	N+PV	N+PV+DG	N+PV+B (baseline)
Capital Costs	1	0	0
Carbon Emissions	0	-1	0
Technology Maturity	1	1	0

The weighting criteria are applied and matrix columns are summed and normalized (Tables 4.4a, 4.4b, 4.4c) . The normalized sums are then summed across each matrix to find the resulting optimal generation resource combination.

Table 4.4: Weighted case Study 1 Pairwise Comparison Matrices: (a) N+PV Baseline, (b) N+PV+DG Baseline, and (c) N+PV+B Baseline

(a) Case Study 1 Pairwise Comparison Matrix (N+PV Baseline), weighted

	N+PV (baseline)	N+PV+DG	N+PV+B
Capital Costs	0	-0.4762	-0.4762
Carbon Emissions	0	-0.3333	0
Technology Maturity	0	0	-0.1905
Sum	0	-0.8095	-0.6667
Normalized Sum	1	0	0.1765

(b) Case Study 1 Pairwise Comparison Matrix (N+PV+DG Baseline), weighted

	N+PV	N+PV+DG (baseline)	N+PV+B
Capital Costs	0.4762	0	0
Carbon Emissions	0.3333	0	0.3333
Technology Maturity	0	0	-0.1905
Sum	0.8095	0	0.1429
Normalized Sum	1	0	0.1765

(c) Case Study 1 Pairwise Comparison Matrix (N+PV+B Baseline), weighted

	N+PV	N+PV+DG	N+PV+B (baseline)
Capital Costs	0.4762	0	0
Carbon Emissions	0	-0.3333	0
Technology Maturity	0.1905	0.1905	0
Sum	0.6667	-0.1429	0
Normalized Sum	1	0	0.1765

Summing the normalized sums, N+PV has a score of 3, N+PV+DG has a score of 0, and N+PV+B has a score of 0.529. Since there is a clear winner, the down-selection is complete. The resulting proposed configuration for Case Study 1 is nuclear and solar coupled to serve a variable community grid load and the electrolyzer facility. Further analysis of this system will follow in Chapter 5.

4.2.2 Case Study 2 Down-selection

In Case Study 1, technology options and evaluation criteria were limited for ease of demonstration. For the second case study, a more complex example is presented using the following prompt:

An energy provider in conjunction with industrial engineering partners in the Gulf Coast of Texas is considering multiple avenues for reducing carbon emissions for a local grid and nearby non-grid energy end-uses for deep decarbonization via a nuclear-renewable hybrid energy system. While serving a local community grid is a priority, the collaborative is interested in implementing other decarbonized end-uses, including a data center, an electrolytic hydrogen production facility, or a desalination plant. The group is also interested in thermal energy storage applications to improve system reliability and efficiency.

Given the solar and wind resources available in the region and the possibility of diverting thermal energy from the nuclear plant for storage, the group is considering the following generation technology combinations:

1. Nuclear + Solar PV (N+PV)
2. Nuclear + Solar PV + Wind (N+PV+W)
3. Nuclear + Solar PV + Diesel Generator Backup (N+PV+DG)
4. Above combinations + Thermal Energy Storage (TES)

The customer is willing to pay a premium for near-term decarbonized energy. However, the group is concerned with minimizing land use over minimizing costs due to local restrictions. In their evaluation of which system configuration to choose, they are considering five factors:

1. Capital costs

2. O&M costs

3. Land use

4. Carbon emissions

5. TRL and extent of deployment

When considering prioritization of criteria, capital and O&M costs are of equal importance. They are less important than land use and carbon emissions. They are much less important than TRL/extent of deployment. Land use is less important than carbon emissions, and much less important than TRL/extent of deployment. Low carbon emissions are of equal importance to TRL/extent of deployment. These priorities are consistent across both the end-use option and the generation resource technologies.

Progressing through the framework steps as defined previously, one can use the group's business mission to identify end-use technology combinations: 1) grid electricity + electricity to serve a data center, 2) grid electricity + electrolytic hydrogen production, and 3) grid electricity + desalination. There does not appear to be additional requirements imposed on the end-use loads, and thus all three options proceed through the framework.

Next, the details in the prompt are used to build a prioritization matrix with the five evaluation criteria under consideration (Table 4.5). Criteria weights are given in the "normalized sum" row, indicating that TRL/extent of deployment is the most important criterion, followed by carbon emissions, land use, and costs.

Next, end-use technology options are investigated via pairwise comparison matrices. Three comparison matrices are needed since there are three possible options, with each technology option set as the baseline. Recall that for these matrices, a score of "1" indicates stronger or more preferred performance, so in the case of costs, a lower cost

Table 4.5: Case Study 2 Criteria Prioritization Matrix

	Capital Costs	O&M Costs	Land Use	Carbon Emissions	TRL/ Extent of Deployment
Capital Costs	1	1	2	2	4
O&M Costs	1	1	2	2	4
Land Use	.5	.5	1	2	4
Carbon Emissions	.5	.5	.5	1	1
TRL/Extent of Deployment	.25	.25	.25	1	1
Sum	3.25	3.25	5.75	8	14
Normalized Sum	0.0949	0.0949	0.1679	0.2336	0.4088

will result in a higher score. Tables 4.6a, 4.6b and 4.6c detail the unweighted pairwise comparison matrices.

Next, criteria weighting factors are applied to these three matrices , values are summed across columns and normalized (available in Appendix A Tables A.1a, A.1b, and A.1c). Adding together normalized sums across each matrix results in Grid + Data Center having a score of 3, Grid + Electrolyzer having a score of 0, and Grid + Desalination has a score of 1.70. Thus, the framework suggests that the Grid + Data Center option is preferred. This option benefited from advanced technology maturity as well as low land use. Note that because capital costs are not the highest priority in this case, electrolyzers did not necessarily benefit from having a lower capital cost per kW (as suggested by literature) compared to data centers and desalination plants.

In this case, there is a distinct priority candidate option. However, if multiple options had close final rankings, the process would repeat with completing pairwise comparison on a 1-5 scale instead of the used 0, -1, and 1 scale.

With the end-use loads selected, generation resources will be determined next. The above analysis suggests that a N-R HES serving both a local grid, and providing behind-the-meter energy directly to a data center is a potential optimal end-use. This result can inform certain requirements for the generation resource technologies. Since

Table 4.6: Unweighted Case Study 2 End-Use Pairwise Comparison Matrices: (a) Grid + Data Center baseline, (b) Grid + Electrolyzer baseline, and (c) Grid + Desalination baseline.

(a) Case Study 2 End-Use Pairwise Comparison Matrix (Grid + Data Center Baseline), unweighted

	Grid + Data Center	Grid + Electrolyzer	Grid + Desal Plant
Capital Costs	0	1	1
O&M Costs	0	1	-1
Land Use	0	-1	-1
Carbon Emissions	0	0	0
TRL/Extent of Deployment	0	-1	0

(b) Case Study 2 End-Use Pairwise Comparison Matrix (Grid + Electrolyzer Baseline), unweighted

	Grid + Data Center	Grid + Electrolyzer	Grid + Desal Plant
Capital Costs	-1	0	-1
O&M Costs	-1	0	-1
Land Use	1	0	0
Carbon Emissions	0	0	0
TRL/Extent of Deployment	1	0	1

(c) Case Study 2 End-Use Pairwise Comparison Matrix (Grid + Desalination Baseline), unweighted

	Grid + Data Center	Grid + Electrolyzer	Grid + Desal Plant
Capital Costs	-1	1	0
O&M Costs	1	1	0
Land Use	1	0	0
Carbon Emissions	0	0	0
TRL/Extent of Deployment	0	-1	0

data centers use electricity, only electrical energy will need to be diverted between the generation resources and the data center. The user should determine if the data center is a critical load needing continuous energy. If so, the nuclear system should be sized to serve maximum community grid and data center loads to ensure reliability. Alternatively, a form of energy storage should be implemented for times where demand surpasses generation resources after being charged with excess energy. Since the group is already interested in thermal energy storage, this technology is included in the down-selection process, and all options that do not contain TES are excluded. Thus, three possible generation technology combinations remain:

1. Nuclear + Solar PV + Thermal Energy Storage (N+PV+TES)
2. Nuclear + Solar PV + Wind + Thermal Energy Storage (N+PV+W+TES)
3. Nuclear + Solar PV + Diesel Generator Backup + Thermal Energy Storage (N+PV+DG+TES)

Three pairwise comparison matrices are created (Tables 4.7a, 4.7b, 4.7c).

Table 4.7: Unweighted Case Study 2 Generation Pairwise Comparison Matrixces: (a) N+PV+TES baseline, (b) N+PV+W+TES baseline, and (c) N+PV+W+DG+TES baseline.

(a) Case Study 2 Generation Pairwise Comparison Matrix (N+PV+TES baseline), unweighted

	N+PV+TES	N+PV+W+TES	N+PV+DG+TES
Capital Costs	0	-1	-1
O&M Costs	0	-1	-1
Land Use	0	-1	-1
Carbon Emissions	0	0	-1
TRL/Deployment Extent	0	0	0

(b) Case Study 2 Generation Pairwise Comparison Matrix (N+PV+W+TES baseline), unweighted

	N+PV+TES	N+PV+W+TES	N+PV+DG+TES
Capital Costs	1	0	1
O&M Costs	1	0	1
Land Use	1	0	1
Carbon Emissions	0	0	-1
TRL/Deployment Extent	0	0	0

(c) Case Study 2 Generation Pairwise Comparison Matrix (N+PV+DG+TES baseline), unweighted

	N+PV+TES	N+PV+W+TES	N+PV+DG+TES
Capital Costs	1	-1	0
O&M Costs	1	-1	0
Land Use	1	-1	0
Carbon Emissions	1	1	0
TRL/Deployment Extent	0	0	0

Next, criteria weighting factors are applied to these three matrices , values are summed across columns and normalized (available in Appendix A Tables A.2a, A.2b, and A.2c). Adding together normalized sums across each matrix results in N+PV+TES scoring 3, N+PV+W+TES scoring 0.40, and N+PV+DG+TES scoring 0.52. Thus, the framework suggests nuclear plus solar plus thermal energy storage is preferred to serve the grid and data center loads. Although TRL and deployment levels were still the highest priority level, because all options scored comparably on this metric, this criterion was not a distinguishing factor in the evaluation. N+PV+TES benefited from comparatively lower land use and lower costs. N+PV+DG+TES, in particular, fell short due to the introduction of a carbon-emitting technology.

4.3 Chapter Summary

This chapter presented two case study demonstrations of the proposed multi-criteria technology selection framework for N-R HESs. These examples demonstrated the usefulness of the framework to rapidly screen out technology options that do not meet exclusionary requirements and down-select remaining options based on prioritized evaluation criteria. Case Study 2 in particular highlighted how system costs may not be the highest priority if other factors, such as timelines for decarbonization and reduced land use, are more important to the stakeholder group. Comparisons of technology options were completed with the notional, high-level analysis of performance metrics on a per unit basis as identified in Chapter 3. For example, this analysis did not consider geographical influences on capital, O&M, or fuel costs. However, this same framework can be used as more specific performance metrics are determined.

After progressing through the framework on the two prompts discussed, two example systems are identified: nuclear + solar PV serving a community grid load + an electrolyzer and nuclear + solar PV + thermal energy storage serving a community grid load + a data center load. In the next chapter, analysis continues with these two case studies, examining system techno-economic and performance characteristics.

CHAPTER 5: VERIFYING CASE STUDY SYSTEM TECHNO-ECONOMIC CHARACTERISTICS AND BEHAVIOR

5.1 Chapter Introduction

Further modeling and analysis is needed to analyze technical and economic viability once a proposed optimal system is selected. This chapter describes a techno-economic analysis of the two case study systems using relevant software tools. This chapter will describe the use of HOMER Pro and MATLAB-Simulink tools to model the two case study systems identified in Chapter 4. HOMER Pro modeling software is used to analyze the system size and economic considerations. MATLAB-Simulink is used to model power flows to investigate the system's physical behavior. While input parameters of these models use the high-level performance metrics discussed in previous chapters, organizations considering N-R HESs can repeat the methodology with parameters more specific to technology design selections (i.e., costs of a specific model of an SMR developed by a specific technology developer deployed in a specific geographical region). Cost and performance parameters associated with specific technologies in this analysis are not those confirmed for actual realized systems, nor are they representative of any specific technology vendor's designs. Parameters used are based off of high-level information presented in Chapter 3 to understand general system techno-economics and behavior.

5.2 HOMER Pro Methodology Description and Results

While the proposed technology selection framework does not assume economic considerations are always the highest priority, system costs will need to be assessed before any real system is implemented, even if the proposed system does not necessarily need to be lowest cost. Therefore, it is prudent to perform a more detailed economic analysis of the example system configurations identified in Sections 4.2.1 and 4.2.2.

Multiple tools exist to model and optimize economics of hybrid energy systems and microgrids. Tools developed at various national laboratories include the Distributed Energy Resources Customer Adoption Model (DER-CAM), the Microgrid Design Toolkit (MDT), the Renewable Energy Optimization (REopt) tool, and Hybrid Optimization Model for Electric Renewables (HOMER) [110]. NREL's System Advisor Model (SAM) can also be used to analyze hybrid energy systems, although ability to represent nuclear is limited [111]. For this analysis, the HOMER Pro modeling tool was chosen for its benefits in terms of allowing for rapid builds of hybrid system scenarios, ability to adjust input parameters of each system component, ability to modify a standard library block to represent nuclear, and general ease of use due to a graphical user interface (GUI). HOMER Pro has been used previously to analyze microgrid-scale systems that include a microreactor as a generation resource and one or multiple end-uses, providing a base of work for this research to build from [54, 35, 36].

Originally developed at the National Renewable Energy Laboratory (NREL) and now a commercial product under UL Solutions, the HOMER Pro software optimizes hybrid system resource configurations and component sizes based on cost [112]. HOMER simulates one year of system behavior and considers local solar radiation and wind resources, obtained from NASA, for the location indicated. Solar PV output is calculated per Equation (2.1) and wind output is calculated per the wind turbine's power curve. HOMER's GUI allows users to easily build a microgrid via a block coding interface. HOMER's results include economic attributes such as levelized cost of energy (LCOE), net present costs (NPC), capital expenditures (CAPEX), and annualized operating expenditures (OPEX). Homer uses the following equation for

LCOE:

$$LCOE = \frac{C_{ann,tot} - c_{boiler} H_{served}}{E_{served}} \tag{5.1}$$

Where $C_{ann,tot}$ is total annualized cost of the system, c_{boiler} is the boiler marginal costs, H_{served} is the total thermal load served, and E_{served} is the total electrical load served. In both case study systems, there is no boiler or thermal load block employed, so

$$LCOE = \frac{C_{ann,tot}}{E_{served}} \tag{5.2}$$

is used in the following analysis. The NPC of the system is the present value of all the costs of installing and operating the system over the project lifetime, minus the present value of all revenues the system generates over the project lifetime. HOMER Pro also provides insights into electrical performance and behavior such as total electricity produced and consumed by resources and loads, percent of unmet load, renewable penetration, and a time series of power flows.

In HOMER Pro, a user inputs component blocks for the generation resources serving load blocks. Standard generation component blocks include generators (diesel default), solar PV, wind turbine, energy storage, hydropower, and hydrokineric energy. HOMER Pro also has standard blocks for AC-DC converters, electrolyzers, reformers, hydrogen tanks, and a grid component for non-islanded microgrid operation. Load blocks include electrical loads, thermal loads, and hydrogen loads. HOMER Pro contains a package of standard electrical load shapes, including residential, commercial, industrial, and community, where a user can choose a peak month, as well as peak power for the year. HOMER Pro also contains a controller component, which allows the user to select a specific control algorithm for the simulation. Control algorithms include Charge Cycling (when a generator is required, it operates at full capacity and surplus power charges the storage bank) and Load Following (when a generator is needed, it produces only enough power to meet the demand). In the simulations described, a combination of generator components, load blocks, and Charge Cycle controller are used.

One limitation of HOMER Pro is that it does not contain a standard block representing a nuclear power plant. However, past studies have modified existing blocks to represent nuclear. Methods include defining nuclear as a custom non-renewable resource resembling a wind turbine with continuous power output or as a custom generator, where inputs for diesel generation are replaced by those relevant to nuclear power and uranium fuel [54, 35, 36]. In the following analysis, nuclear is represented as a custom generator.

Capital and O&M costs of the custom generator are adjusted based on the median cost estimates for SMRs in [94]. To represent nuclear's high capacity factor, the generator minimum runtime was set so that the reactor would at full power run all year. "Uranium" was then created as a custom fuel, where the relevant heat rate value was input, and the fuel curve was adjusted to emulate predicted average burnup rates of U.S. SMRs currently under development [113]. The HOMER Pro dispatch strategy is set to Charge Cycle, which makes a generator operate at full power when the primary load requires power from the generator. Excess energy is diverted to secondary loads or storage systems. Table 5.1 details the parameters for a 80 MW nuclear SMR unit represented in both case studies. Values presented as per unit power or energy were scaled appropriately for an 80 MW system.

Table 5.1: Input Performance Parameters for an 80 MW SMR in HOMER Pro

Parameter	Value	Units	Source
Capacity	80,000	kW	assumed
Capital	811,200,000	2024 USD	[94]
Replacement	811,200,000	2024 USD	[94]
O&M	2,980	2024 USD/operating hr	[94]
Minimum Load Ratio	100	%	assumed
Lifetime	60	years	[113]
Minimum Runtime	525,600	minutes	assumed

Table 5.2: Input Fuel Parameters for Custom Uranium Fuel

Parameter	Value	Units	Source
Lower Heating Value	3,900,000	MJ/kg	[114]
Density	19,000	kg/m^3	[115]
Uranium Fuel Price	2,846	2024 USD/kg	[94]
Fuel Curve Y Intercept	0.216	kg/hr	[113], Eq. (5.5)

Properly representing uranium fuel consumption is important for understanding operational costs. Table 5.2 highlights key input parameters established for the custom "Uranium" fuel. Values are representative of low enriched uranium.

In addition to these parameters, a fuel curve is specified to inform the mass of fuel used per hour per rated kW, or in other words, how quickly the generator uses fuel. Fuel usage rate informs annual fuel costs. In this case, it is assumed that the reactor will be refueled on a regular two year schedule, so on a cost level, the slope of the fuel curve will be flat (refueling schedule will not change significantly if the reactor operates at different capacity). Additionally, in this simulation, the reactor operates at constant power output. With the slope of the curve determined, one must simply find the y intercept of the fuel curve, represented by kg of fuel used per hour. To determine this value, reactor burnup rate (BUR) is considered, which is a way to measure the amount of energy produced by uranium in a reactor. It is typically measured in gigawatt-days per metric ton of uranium. Taking this definition, burnup rate can be represented as:

$$\begin{aligned} \text{BUR} &= \frac{\text{(rated capacity [GW])*(operating time [days])}}{\text{(metric tons of Uranium used during operation)} * \eta_{thermal}} \\ &= \frac{\text{(rated capacity [GW])*(days between refuel)}}{\text{(metric tons of Uranium used between refuels)} * \eta_{thermal}} \end{aligned} \tag{5.3}$$

Where $\eta_{thermal}$ is the thermal efficiency of the reactor. If operating time is taken to be the time between refuels, one can then solve for kg of Uranium used between refuels, understanding 1 metric ton is equal to 1,000 kg:

$$\text{kg U used between refuels} = \frac{1000 * (\text{rated capacity [GW]})*(\text{days between refuel})}{(\text{BUR}) * \eta_{thermal}} \tag{5.4}$$

Finally, value is divided by hours between refuels to determine the fuel curve coefficient:

$$\begin{aligned}\text{Fuel Curve Intercept} &= \frac{1000 * (\text{rated capacity [GW]})}{24 * (\text{BUR}) * \eta_{thermal}} \\ &= \frac{(\text{rated capacity [MW]})}{24 * (\text{BUR}) * \eta_{thermal}}\end{aligned} \tag{5.5}$$

Per [113], a representative average burnup rate for various SMRs being developed in the U.S. is 46.1 GWd/ton. Reactor thermal efficiency is taken to be 33.4% [116], and thus the fuel curve y intercept is found to be 0.216 kg/hr. This value is used in the fuel curve table in HOMER Pro when defining the Uranium fuel.

This treatment of nuclear resources will be used when modeling both case study systems. Further system component parameters will be detailed in the following sections, alongside case study results. Across both case studies, new transmission costs are not considered, however, they could influence economics significantly, particularly if systems are not sited nearby existing energy delivery capacity.

System-wide economic parameters were kept as the HOMER Pro default values in both cases: 6% discount rate, 2% inflation rate, 5% annual capacity shortage, and 25 year project lifetime. Both case study systems are modeled in the year 2023 and use associated historical solar profiles.

5.2.1 Case Study 1: HOMER Pro Inputs and Results

Recalling from Section 4.2.1, the Case Study 1 down-selection process resulted in a system that used nuclear plus solar PV to serve a grid load plus a 100 MW electrolyzer. In this case, the electrolyzer serves as a load for excess electricity production. The

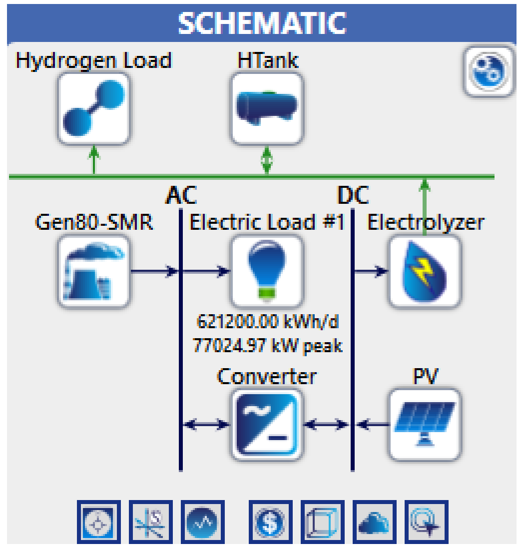


Figure 5.1: Schematic of Case Study 1 N-R HES configuration in HOMER Pro

system is modeled in HOMER Pro to investigate economic and performance aspects of the system. In HOMER Pro, one 80 MW nuclear SMR unit as described above is used, alongside 20 MW of solar PV, represented by the generic flatplate PV block in HOMER Pro. In addition to an electrolyzer block, a hydrogen storage tank and a hydrogen load are also included, representing regular use, discharge, or transport of hydrogen away from the site. The local grid load is represented by the generic "Community" load shape available in the HOMER Pro library emulating a grid with residential and industrial loads (Figure 5.2). This community load has a scaled annual average of 621.2 MWh per day with peak load of 77 MW. This load scale was chosen to align closely to the size of the 80 MW nuclear system to mitigate unmet grid load if peak load coincides with low or no solar output. This system is also sited nearby Charlotte, NC to align with the location of interest in the Case Study 1 prompt. HOMER Pro's generic converter block is used for AC/DC conversions.

Relevant parameters for the solar PV block and electrolyzer block are found in Tables 5.3 and 5.4. For both these resources, only size and cost parameters were adjusted from default to align with costs found in Chapter 3. Note that the electrolyzer replacement costs were selected based on analysis in [77] that indicates that elec-

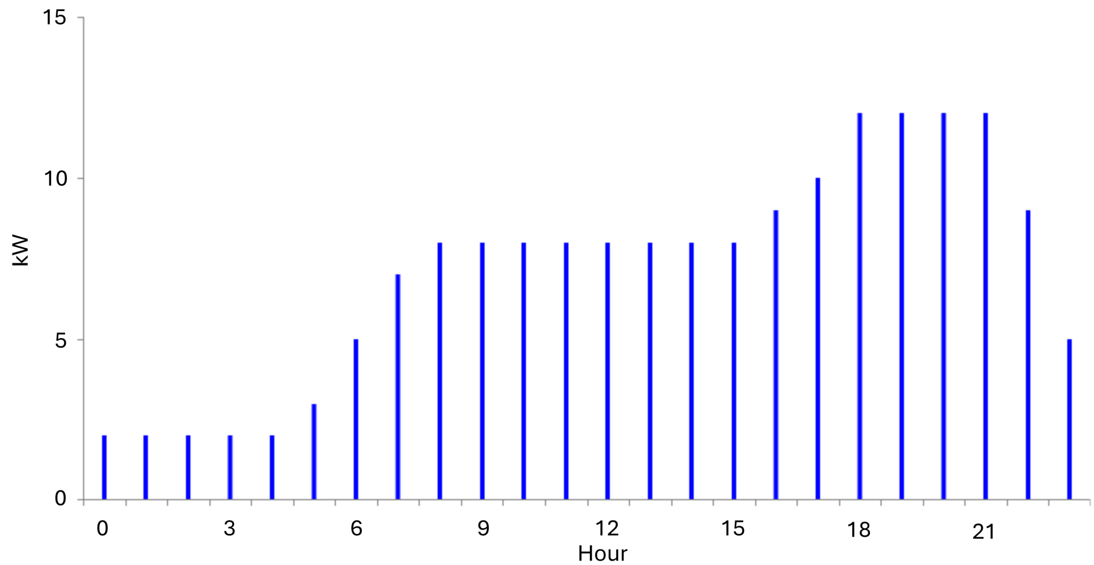


Figure 5.2: Unscaled 24-Hour Community Load Profile in HOMER Pro

trolyzer replacement costs are 11% of capital costs, incurred every 40,000 operating hours. It is assumed that the electrolyzer is operating year round.

Because the electrolyzer is used as a load to capture excess energy, a mechanism is needed to represent hydrogen being used or transported to another location to allow the electrolyzer to run as needed. To do so, a hydrogen tank capable of storing 50,000 kg of hydrogen is included, along with a large hydrogen load that represents the hydrogen being transported away from the N-R HES for use in other applications. Taken from literature on compressed gas above-ground storage costs, the hydrogen tank capital cost and replacement is set to $21.1 million each and O&M costs are set

Table 5.3: Input Performance Parameters for an 20 MW Solar PV System in HOMER Pro

Parameter	Value	Units	Source
Capacity	20,000	kW	
Capital	31,200,000	2024 USD	[94]
Replacement	31,200,000	2024 USD	[94]
O&M	360,000	2024 USD	[94]
time	25	years	default
Derating Factor	80	%	default

Table 5.4: Input Performance Parameters for an 100 MW Electrolyzer in HOMER Pro

Parameter	Value	Units	Source
Capacity	100,000	kW	
Capital	223,000,000	2024 USD	[77]
Replacement	24,530,000	2024 USD	[77]
O&M	11,100,000	2024 USD	[77]
Lifetime	4.6	years	
Efficiency	85	%	

to $62,000 per year [117, 118]. Tank lifetime is set to the default 25 years.

HOMER Pro calculates LCOE based on power delivered to non-electrolyzer loads only. HOMER Pro results thus indicate that this system has an LCOE of $0.475 per kWh, and CAPEX of $1.12 billion, and operating costs of $36.8 million per year. It is noted that the LCOE calculation for this system only includes electricity delivered to the community load. If energy delivered to the electrolyzer is included in this calculation, LCOE would be $0.153/kWh. Net present costs are $1.70 billion. In addition to large upfront expenses for the nuclear SMR, capital costs are also largely driven by the size of the electrolyzer. Capital and operational costs could also be influenced by more specific modeling of hydrogen storage and use beyond the surrogate model used with the hydrogen tank and load in this model.

HOMER Pro provides information on how different resources are used in the system based on the charge controller setting. While the nuclear asset is a constant power resource, solar PV dispatched most days, with a peak renewable penetration (renewable output divided by load) of 20.3%. Figure 5.3 shows this renewable penetration, or instantaneous renewable output divided by load. PV generation is productive during daytime hours, as expected.

HOMER Pro also gives insights into hydrogen production throughout the modeled year. Figure 5.4 shows power to the electrolyzer peaking in morning hours when the community load demand is low, and at a minimum in the evenings when commu-

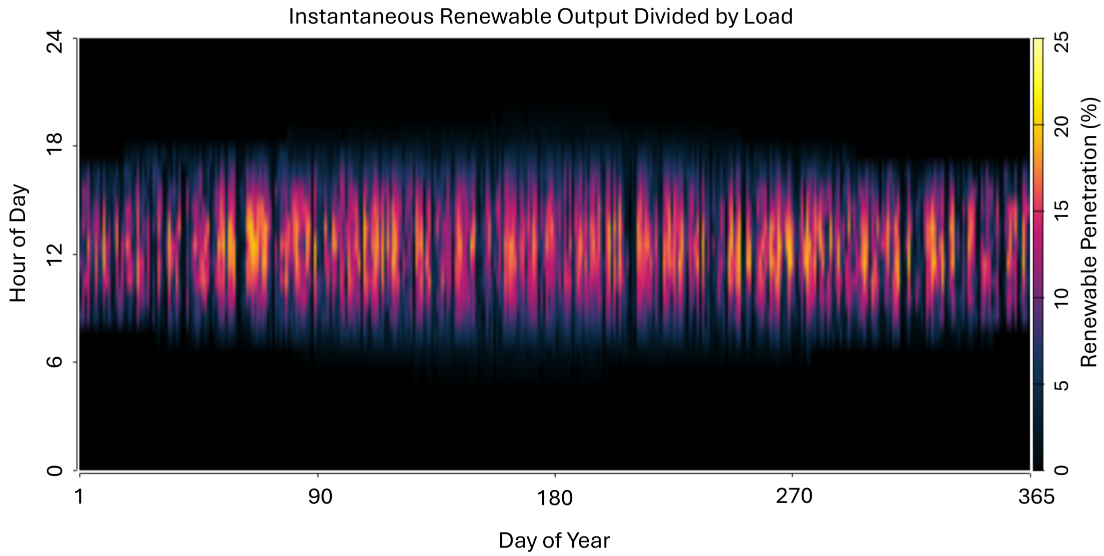


Figure 5.3: HOMER Pro Results for Case Study 1 Renewable Penetration (Instantaneous Output Divided by Load)

nity load demand is highest. Midday hours also sees higher electrolyzer input power, coinciding with higher solar penetration. The model suggests the electrolyzer produced 10,297,502 kg in one year. The calculated levelized cost of hydrogen (LCOH) is $10.5/kg, which is within $2 of the LCOH values for PEM electrolysis given in [94] after adjusting to 2024 dollar values. Note that due to its unique configuration, this case study system has higher costs of electricity than what is assumed in [94], so the increased LCOH result is expected.

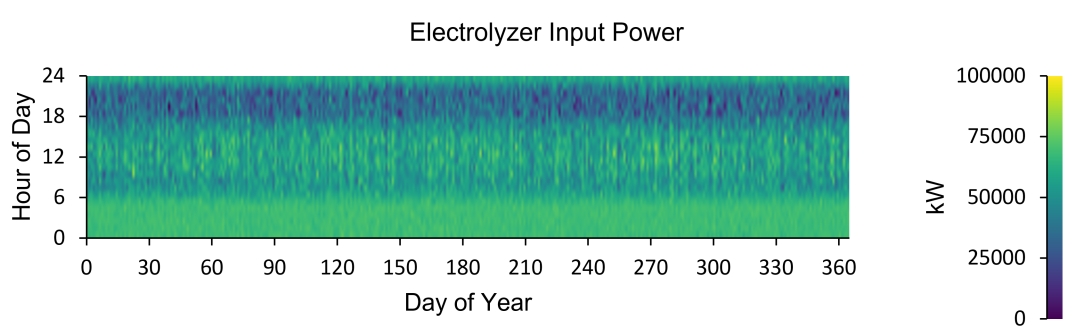


Figure 5.4: HOMER calculated Electrolyzer Input Power

The dispatch decisions HOMER Pro made can be visualized via the HOMER Pro-calculated time series plot in Figure 5.5. This Figure shows four select days (July 1-4, 2023) of hourly power resource output and loads served. As discussed above, the electrolyzer is successful in using excess electricity produced by the SMR and solar PV resources. In the mornings, the electrolyzer load increases when the community load is lower. Electrolyzer input also increases during midday when PV output is peaked. Throughout the simulation year, there is zero unmet electrical load, meeting the system requirement set in the prompt. Over the course of the year, 32.2% of the energy is delivered to the community load, while 67.8% of the energy is consumed by the electrolyzer.

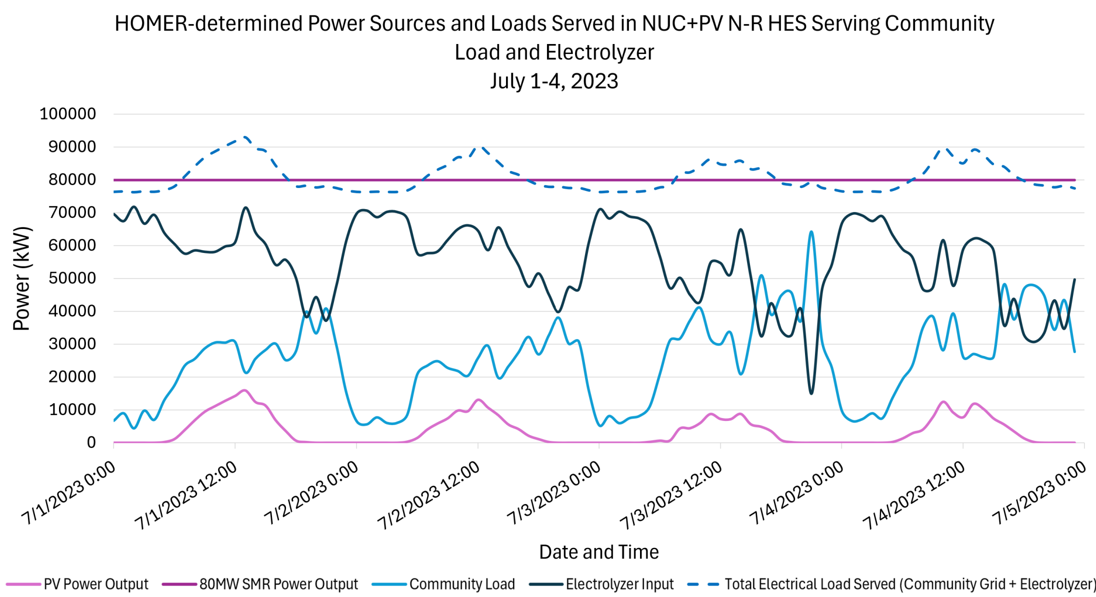


Figure 5.5: HOMER Pro-calculated timeseries of power sources and loads for select days in simulation year. Solar PV (light pink) dispatches during daytime hours as expected and the 80 MW SMR (dark pink) has constant power output. The community load (ligher blue) is low in the mornings, then increases throughout the day until the evenings and nights. During times of low community load demand, particularly when PV is productive, the electrolyzer demand is high and vice versa, indicating that the electrolyzer is working efficiently as a resource for capturing excess power.

5.2.2 Case Study 2: HOMER Pro Inputs and Results

Per Section 4.2.2, the second case study N-R HES involves nuclear, solar, and thermal energy storage resources serving a community grid load and a large data center with static power demand in Texas. In this case, neither load is deferrable or is reserved to use excess energy. Instead, the thermal energy storage system is used to capture excess energy for use within the system at a later time. To simulate this system in HOMER Pro, the same parameters representing nuclear and solar resources in Case Study 1 are used, including capacities of 80 MW SMR power and 20 MW of solar PV capacity. The community load size is maintained as 621.2 MWh per day with peak load of 77 MW. The system is sited outside of Houston, TX to align with the prompt and capture relevant solar irradiation data.

The data center in this scenario is a required electric load, and thus, is represented in HOMER Pro as a non-deferrable electric load with an "industrial" (flat) load shape (Figure 5.6). This load is scaled to a 50 MW (or 1,200 MWh per day) average. An introduced 10% day-to-day random variability results in a 91.7 MW peak load. HOMER Pro does not allow electrical loads to be assigned a capital or O&M costs. Instead, to capture the cost of building and operating a new data center, a system fixed capital cost of $675 million is set, as well as a system fixed O&M cost of $37.5 million per year (as suggested per median values in [85]). An assumed replacement cost of 5% of system capital costs is implemented every 5 years. Because there is no place to input system-wide replacement costs in HOMER Pro like there is for capital costs, the data center replacement cost is included in the replacement costs of the solar block, which was assumed to not need replacement in the 25 year project timeline.

Another limitation of HOMER Pro is that it does not have component blocks for thermal energy storage technologies, although it has a suite of battery storage technology block options. In this scenario, it is assumed that the TES system is

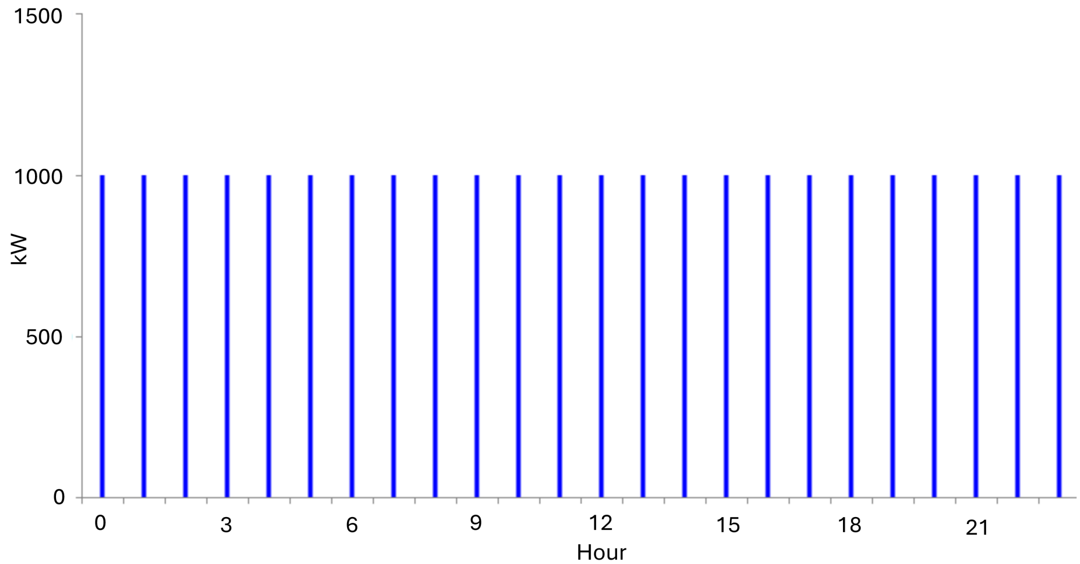


Figure 5.6: Unscaled 24-Hour Industrial Load Profile in HOMER

integrated within the nuclear plant boundary, meaning that heat from the reactor will be diverted to the TES during times of low power demand, but after dispatched will be converted into electricity before delivery to the all-electric end uses in this system. It is assumed additional balance of plant infrastructure is not required beyond that of the reactor. HOMER Pro does have capabilities for modeling boilers or waste heat ratios to serve thermal loads, however, this approach does not allow the thermal energy captured in the thermal load to be converted to electricity to power the electrical loads. Thus, this analysis is limited to using a battery block to best represent thermal energy storage within a system that has only electric loads. It is assumed that thermal energy produced by the nuclear reactor diverted to the TES before power conversion, stored, and then later used to heat steam or other coolants in the power conversion system to generate electricity, can be represented as electrical energy produced at the back end of the conversion system diverted to a battery for storage. Thus, HOMER Pro's default 1 kWh lithium ion battery is used as a surrogate for thermal energy storage. The full system schematic is shown in Figure 5.7.

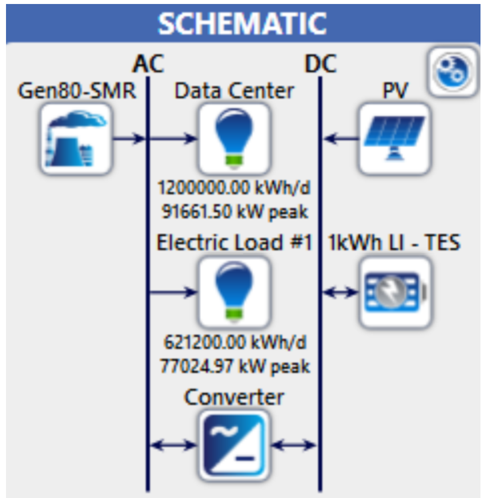


Figure 5.7: Schematic of Case Study 2 N-R HES configuration in HOMER. A generic lithium ion battery is used as a surrogate for thermal energy storage.

One major consideration is the difference in round trip efficiency (RTE) between battery storage and thermal energy storage. HOMER Pro's lithium ion battery block has an RTE of 90%. Per [119], the molten salt TES RTE is taken to be 42%. Thus, it is known that HOMER Pro will size the system 2.14 times smaller than what it will need to be if molten salt TES is used. To correct for this, input costs are adjusted by a factor of 2.14. The $36.70/kWh CAPEX [105] is scaled to $78.6/kWh and the $7.7/kWh per year O&M costs are scaled to $16.5/kWh per year. Once calculated, HOMER Pro's automatic output sizing will be adjusted by 2.14 times to find the actual capacity needed to serve the system. The storage block is set to have an initial state of charge of 80%.

To minimize unmet load, HOMER Pro calculates that 522 MWh of lithium ion storage is needed, meaning that after scaling for efficiency, a molten salt TES system with capacity of 1,117 MWh is needed to properly serve the system. This size system is aligned with TES systems analyzed in literature [105] [108], so it is accepted that this result is reasonable.

HOMER Pro results indicate that this system has an LCOE of $0.263 per kWh. This LCOE value considers electricity consumed by both the community load and the data center load. The system has a CAPEX of $1.59 billion, and operating costs of $73.8 million per year. Net present costs are $2.75 billion. Capital costs are largely driven by the upfront cost of the SMR and the high data center costs. While this case study system has higher costs than Case Study 1, it is noted that the group considering this N-R HES did not have costs as their top priority. In this scenario, the peak renewable penetration is 68.3%, although this peak value appears to be an outlier (Figure 5.8).

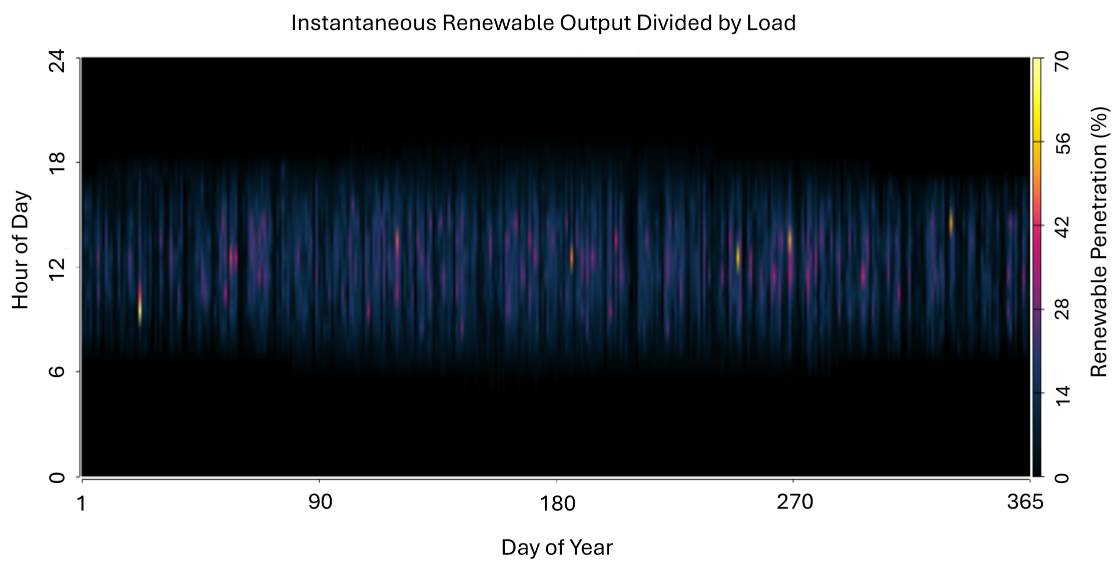


Figure 5.8: HOMER Results for Case Study 2 Renewable Output Divided by Load

Figure 5.9 shows four select days of power source generation, load consumption, and storage input/output as calculated by HOMER Pro. HOMER Pro does not distinguish between the two electrical loads (community grid and data center), so the sum of both loads are represented in a single data series. HOMER Pro does provide insights into the battery operation (Figure 5.10). As seen on July 3rd and 4th most clearly, when electrical demand is low, the battery charges, then dispatches when electrical demand is high. This allows the system to more effectively use the solar and nuclear energy. However, it is noted that during many hours on July 1st and

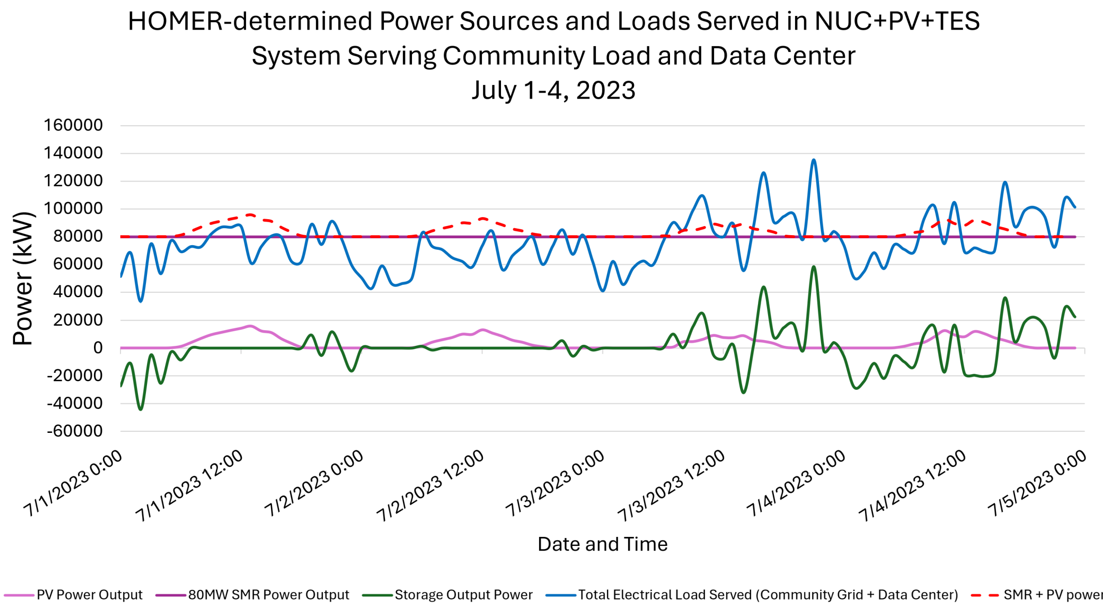


Figure 5.9: HOMER Pro-calculated timeseries of power sources and loads for select days for Case Study 2. Light pink represents PV output. The SMR output (dark pink) is constant at 80 MW. When total SMR and PV generation (red dash) exceeds total electrical load (blue), energy either directed to the storage system if the system is not at capacity, or it is let to waste. A negative value for "Storage Output Power" (green) indicates the storage system is charging, while a positive value indicates dispatch.

2nd, and until hour 6 on July 3rd, the storage system does not charge or dispatch and remains at 100% state of charge. This indicates excess electricity production in the system. Further refinement of storage representation and sizing optimization may be needed to reduce excess electricity. However, some amount of excess energy may be a tradeoff for the benefits of not implementing an oversized storage system. There is more noise in the total electrical load served in this example compared to Case Study 1 as both the community load and data center load each have random daily variability embedded in their load profiles (10% each). In Case Study 1, only the community load had daily random variability.

Unmet electrical load is 0.05%, which is sufficiently low to meet service requirements. Tools with more sophisticated dispatch models and treatment of thermal energy storage could help refine system sizing to further reduce unmet loads.

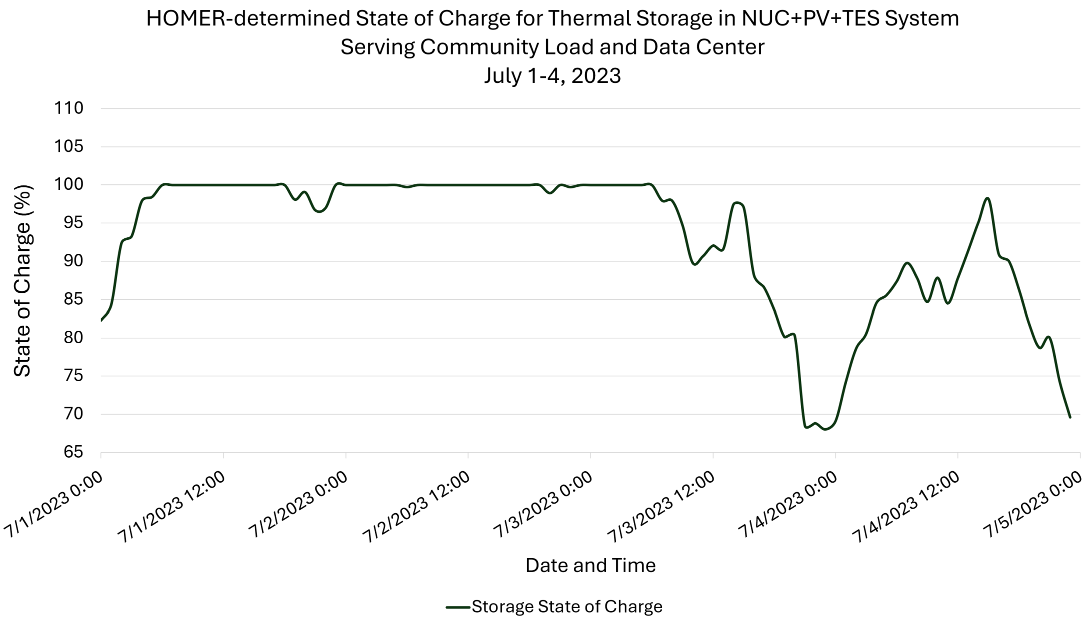


Figure 5.10: HOMER Pro-calculated timeseries of TES state of charge for select days for Case Study 2. The extended hours where SOC is at 100% on July 1st and 2nd indicate that the amount of energy generated in the system exceeds both load demands and the amount of energy the storage system's capacity.

5.3 MATLAB-Simulink Methodology and Results

While HOMER Pro is a useful tool for detailed analysis of system economics and provides information on system dispatch behavior, it cannot rigorously capture system physical behavior or perform sophisticated power flow analysis. Thus, MATLAB-Simulink is implemented to use its suite of multi-physics modeling tools to develop a physical system model and confirm power flow results from generation resources to loads.

MATLAB-Simulink is a model-based design tool with a block diagram environment that allows users to design and simulate systems [120]. Specifically, Simscape, which operates inside the MATLAB-Simulink environment, allows for the rapid creation of models of physical systems across many domains [121]. For this work, the Simscape Specialized Power Systems library is used to simulate one day of behavior of each case study N-R HES via a simplistic model. A modified version of the model provided in

[122] is used for both case studies. This model represents a simple microgrid via a one-line diagram using blocks representing solar PV, a diesel generator, and an energy storage system serving a static and variable load. The original model includes a grid connection for input power; however, this connection is removed as the case study systems only consider isolated power generated from specific nuclear and renewable installations. The following sections detail how [122] is further modified to represent each case study system and discuss results. For both case studies, one day or 24 hours of system behavior is modeled. Time series inputs for hourly community load and PV production are calculated from the HOMER Pro results presented in Section 5.2 and represent hourly averages over the full simulation year.

5.3.1 Case Study 1: MATLAB-Simulink Configuration and Results

Case Study 1 has an 80 MW SMR and a 20 MW solar PV system serving a variable community electric load while all excess energy is diverted to an electrolyzer for hydrogen production. The representative model created of this system in MATLAB-Simulink is shown in Figure 5.11. The system's PV power output is related to the system's site near Charlotte, NC. Specific information on the Simulink model configuration follows.

Modifications to [122] begin by configuring the community load the N-R HES must serve. This model uses a Simple Three Phase Load block with input dynamic load control to represent variable loads (Figure 5.12). Inputs to this subsystem are a time series of active power. The annual AC Primary load is pulled from HOMER Pro results from this case study to characterize the community grid load. Hourly loads are averaged for each hour of day over the entire simulation year. These averages are used in a 1-D Lookup Table block that feeds the variable load active power input for 24 one-hour timesteps.

On the generation side, this system includes both an 80 MW SMR and a 20 MW solar PV array. The PV array is represented via a simple solar inverter (Figure 5.13),

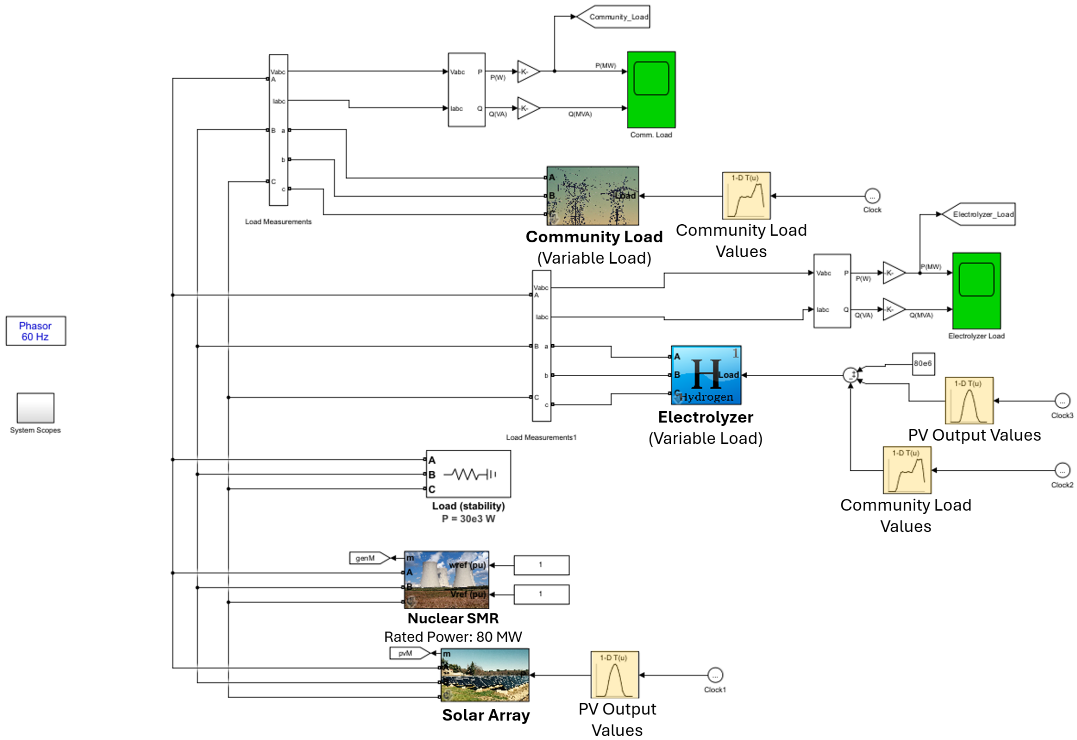


Figure 5.11: Full MATLAB-Simulink system built to represent Case Study 1 system: a nuclear SMR and solar PV serving a variable community load and an electrolyzer.

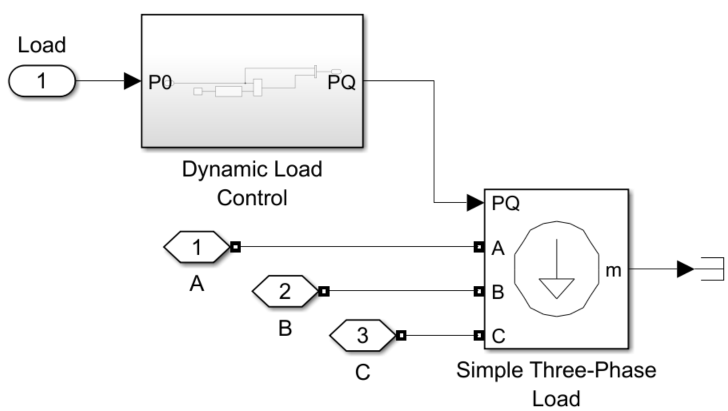


Figure 5.12: Three Phase Dynamic Load used to represent a variable community load.

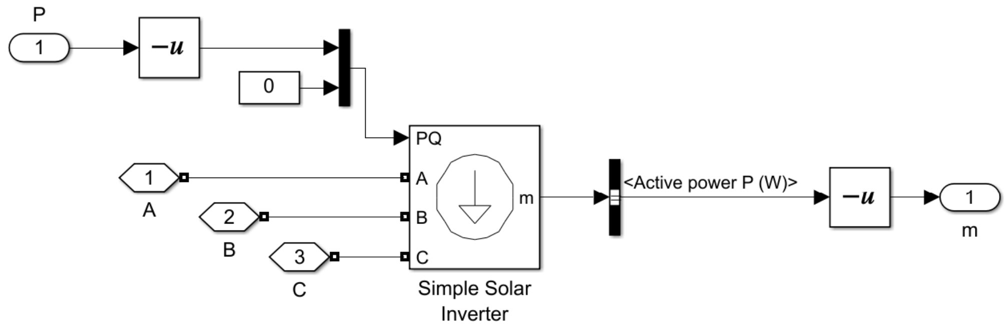


Figure 5.13: Simple Solar Converter implemented via a Three Phase Dynamic Load block in MATLAB-Simulink. Input to this system is the solar PV active power, known from HOMER Pro calculations of solar output.

multiplying outputs from a three-phase dynamic load by a gain of -1 to represent power output. The subsystem takes values representative of the desired power production as input. For this case, average hourly PV production is found via HOMER Pro calculations across the simulation year. This hourly averaged PV output value is imported into a 1-D Lookup Table block and is used as the input to the PV block in MATLAB-Simulink. Future iterations of this model can use Simulink's solar array block to recalculate power output based on local solar irradiance.

The SMR is represented by a subsystem analogous to a diesel generator, with a Synchronous Machine block controlled by a diesel generator governor and excitation system (Figure 5.14). This subsystem is set to have an 80 MW power capacity. This generator can ramp power output up and down to maintain a 60 Hz system frequency. To have this generator behave like a nuclear reactor with constant power output, the electrolyzer block is modified so that excess electricity is diverted to it.

Like the community load, in this case study, the electrolyzer is also represented by a simple subsystem with a Three-Phase Dynamic Load, identical to that in Figure 5.12 except for the power load input parameter. Understanding that the electrolyzer is being used as a load to capture excess energy production, the load as a function of

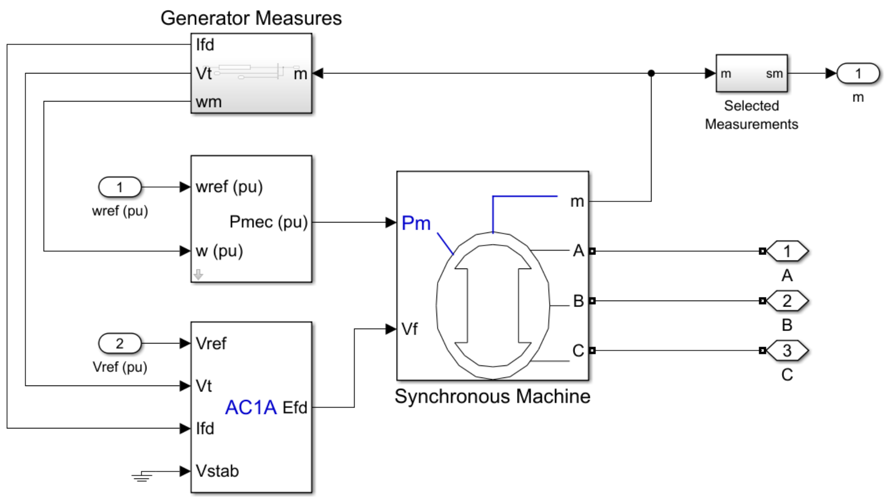


Figure 5.14: The nuclear resource is represented in MATLAB-Simulink with a diesel generator and governor system. Controls on the electrolyzer load will keep this subsystem's power output constant.

time t is:

$$\begin{aligned}\text{Electrolyzer Load}(t) &= \text{Total System Generation}(t) - \text{Community Load}(t)\\ &= \text{Nuclear Output}(t) + \text{PV output}(t) - \text{Community Load}(t)\\ &= 80\text{MW} + \text{PV output}(t) - \text{Community Load}(t)\end{aligned} \tag{5.6}$$

PV output(t) and Community Load(t) are known from average hourly timesteps through this representative day. Thus, the electrolyzer load value is known and is implemented as shown in Figure 5.15. Implementing this load configuration on the electrolyzer allows the generator subsystem to remain at a constant 80 MW as desired. Finally, a small 30 kW static Three-Phase RLC Load block is included in the system to maintain system stability.

To investigate system behavior, power outputs from the two generation resources and power flows to the two dynamic loads are analyzed (Figure 5.16). The first two hours of the simulation are omitted to discard outlier values related to the initial-

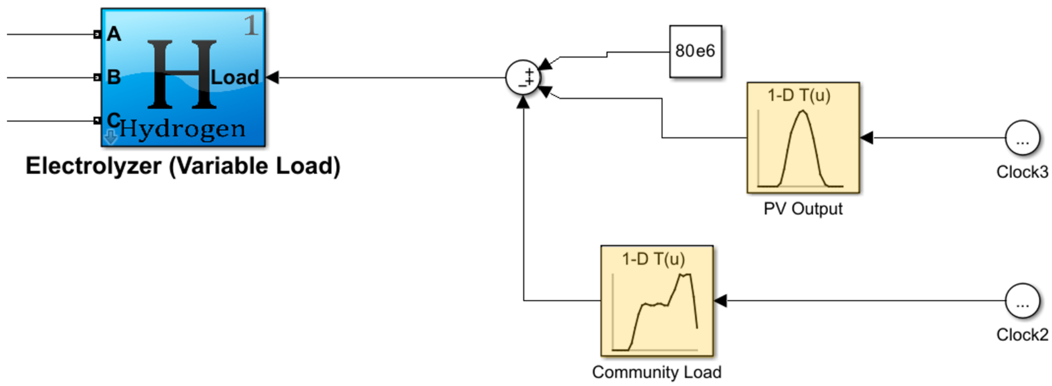


Figure 5.15: The electrolyzer load value is configured as the difference between system generation and the community load so that the 80 MW nuclear reactor maintains constant power output and excess electricity is delivered to the electrolyzer.

ization of numerical calculations. The system behaves as suggested by the HOMER Pro load flow analysis. Because the SMR output remains constant throughout the day, the electrolyzer load decreases with increased community load and increases with decreased community load and increased PV output. The system does experience a frequency drop at the beginning of the simulation, where the frequency is below 60 Hz for the first four initial hours, although it does stabilize around 60 Hz by hour 6 (Figure 5.17). This drop may also be caused by numerical calculation initialization or the electrolyzer and community loads forcing non-steady state behavior on the generator control system upon startup. Future work can further investigate this initial frequency drop, along with faults and transients as power is diverted between loads.

5.3.2 Case Study 2: MATLAB-Simulink Configuration and Results

Case Study 2 investigates a similar N-R HES configuration as the previous study, except the system must serve a required 50 MW data center load in addition to the community grid load. Thermal energy storage is also incorporated. The system is sited outside of Houston, Texas, so solar PV output is altered based on relative weather conditions. In this case study model (Figure 5.18), the nuclear resource,

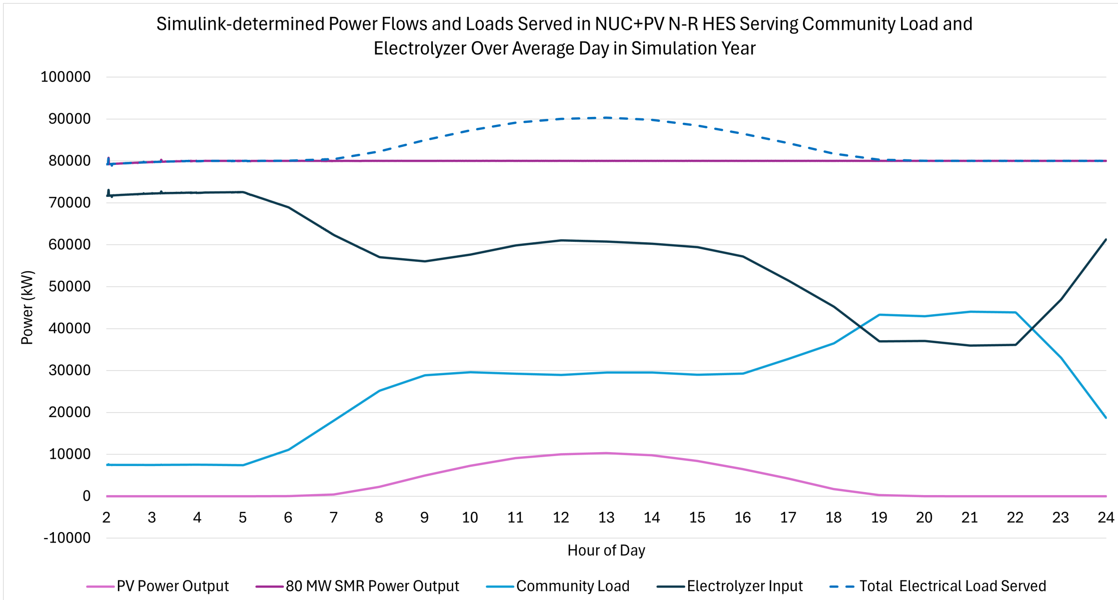


Figure 5.16: Power flows and loads served as a result of the MALAB-Simulink model of the Case Study 1 N-R HES on a time-averaged day in the simulation year. PV power output (light pink) is productive only during daylight hours. The 80 MW SMR (dark pink) has constant power output. The community load (light blue) increases throughout the day and then declines in the late hours. Throughout the simulation day, the electrolyzer load (navy) captures excess energy not needed to serve the community load: electrolyzer demand is high when the community load is low and vice versa. This system allows the total electrical load served (blue dash) to equal the total power generated, indicating efficient use of energy resources.

community load, and solar array are represented in the same way as in Case Study 1. However, input lookup tables for average hourly community load and average hourly PV output are updated to values based on HOMER Pro output for Case Study 2. A static Three-Phase Series RLC Load with 50 MW of active power represents the data center load. Since this model represents an average day, random variability of the data center load is not investigated and thus is kept as a static 50 MW load throughout the simulation day.

This system implements a thermal energy storage system to absorb excess energy production and dispatch energy when generation resources are not producing sufficient energy. While MATLAB-Simulink does have capabilities for modeling thermal systems and heat flows, integrating the Thermal Library with the Specialized Power

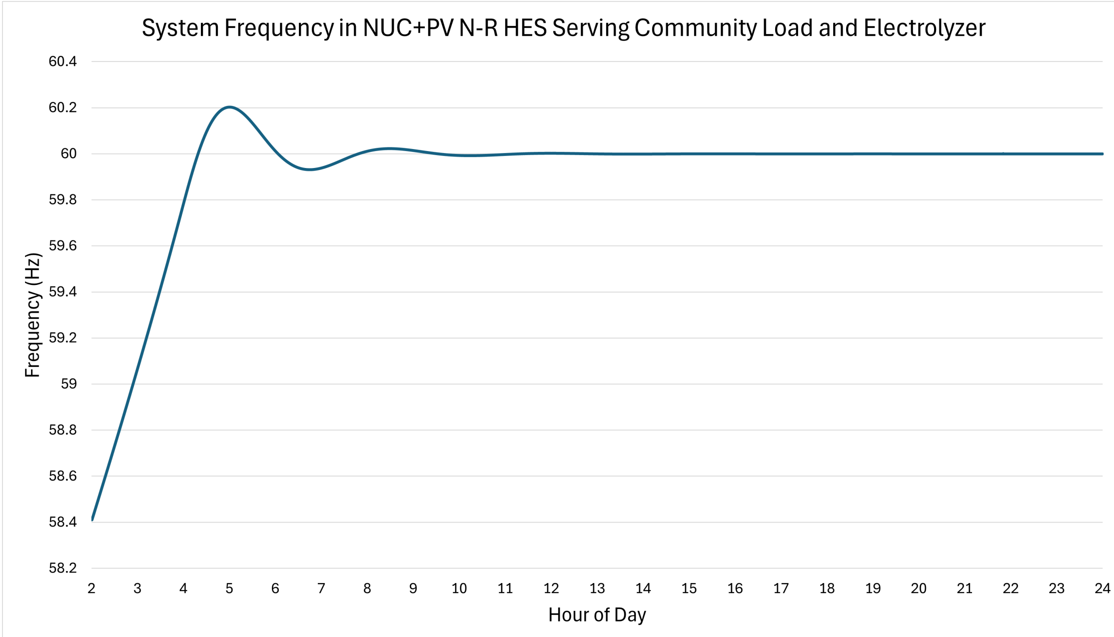


Figure 5.17: Case Study 1 model system frequency throughout the simulation day.

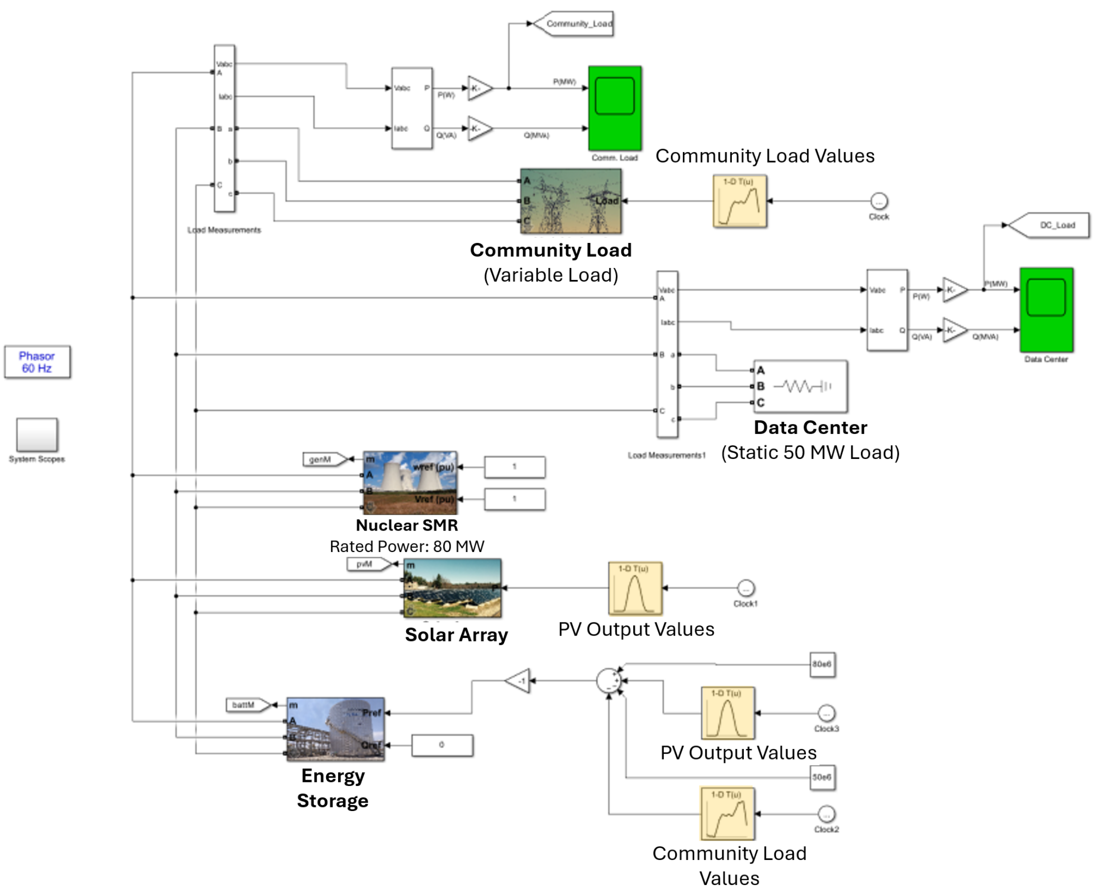


Figure 5.18: Full MATLAB-Simulink system built to represent nuclear and solar PV serving a variable community load and a 50 MW data center.

Systems Library is beyond the scope of this work. Instead, per [122], a simplistic energy storage system is represented by a Three-Phase Dynamic Load block whose load considers the storage system's charge limits (Figure 5.19). When there is excess energy, the storage system charges. When the system demands more energy than the SMR or solar PV provides, the storage system discharges. It is assumed that with proper tuning of efficiency parameters, a thermal energy storage that would sit before the nuclear steam cycle system is analogous to an electrical energy storage system that captures energy after the power conversion system.

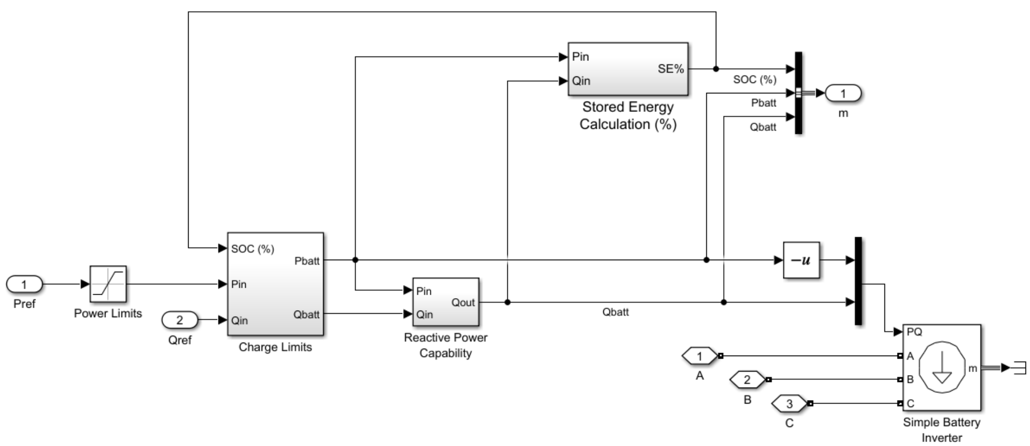


Figure 5.19: The thermal energy storage system is represented by a surrogate model of an electrical three-phase load that produces negative power when charging and outputs positive power when dispatching.

Component parameters are adjusted to match the characteristics of the energy storage system in MATLAB-Simulink. The rated system energy capacity is set to 1,117 MWh, and the rated power is set to 131 MWh (assuming an 8.5-hour dispatch time, representative of systems analyzed in [105]). The overall system efficiency is set to 42%, the upper and lower charge limits are 100% and 0%, respectively, and the initial state of charge is set to 80%.

Similar to the electrolyzer input power in Case Study 1, the power to or from the energy storage system is based on whether the SMR or solar PV produces excess or insufficient energy. When measured in the reference frame of power flows to the community or data center load, the power from the storage system is negative when it absorbs energy and positive when the system dispatches energy. Thus, the storage system's power output at time t is configured as:

$$\begin{aligned}\text{Storage Energy Out}(t) &= -(\text{Total System Generation}(t) - \text{Total System Loads}(t)) \\ &= -(\text{Nuclear Output}(t) + \text{PV output}(t) \\ &\qquad - \text{Data Center Load}(t) - \text{Community Load}(t)) \\ &= -(80\text{MW} + \text{PV output}(t) - 50\text{MW} - \text{Community Load}(t))\end{aligned} \tag{5.7}$$

PV output(t) and Community Load(t) are known from HOMER Pro results for hourly average time steps. The input load per Equation (5.7) is implemented for the storage system as seen in Figure 5.20. When implemented, the generator representing the SMR generates a constant 80 MW throughout the day.

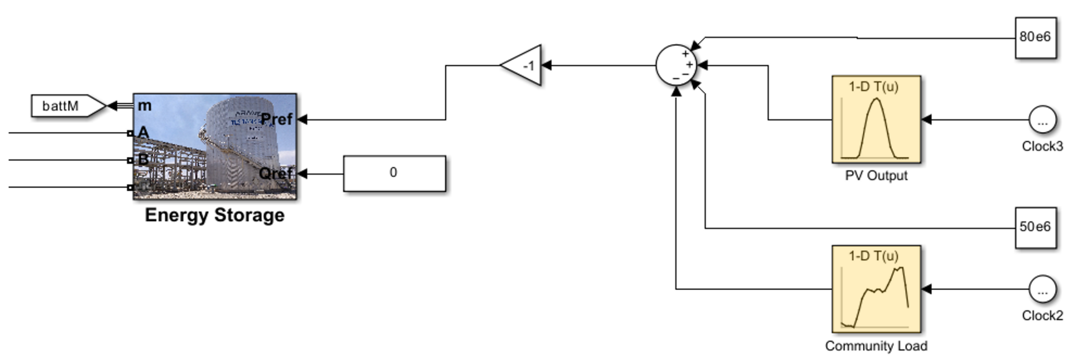


Figure 5.20: Storage System power input is set so that the system charges when total system generation excess total system loads and dispatches when the system demands more power than the generation resources can provide. This configuration allows the SMR block to run at a constant 80 MW as desired.

Power flows from the SMR and PV blocks to the community and data center loads as well as power flows to and from the storage system are investigated (Figure 5.21).

As expected, the storage system charges in the morning and afternoon hours until hour 17 when the electricity demand is lower than the nuclear and PV generation. When demand exceeds power generation from hour 17 to 23, the storage system dispatches energy.

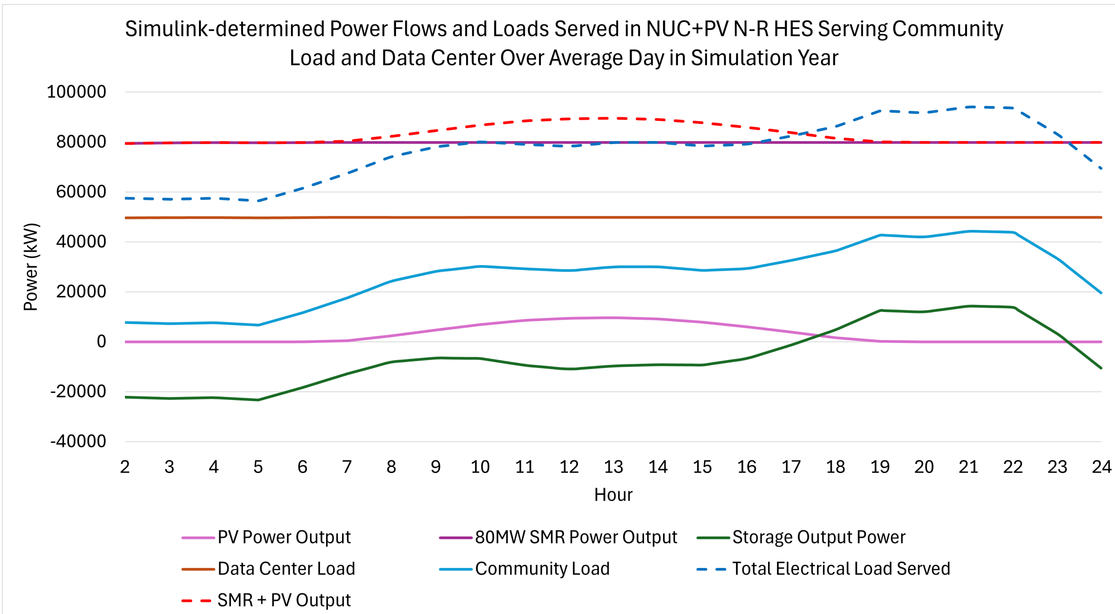
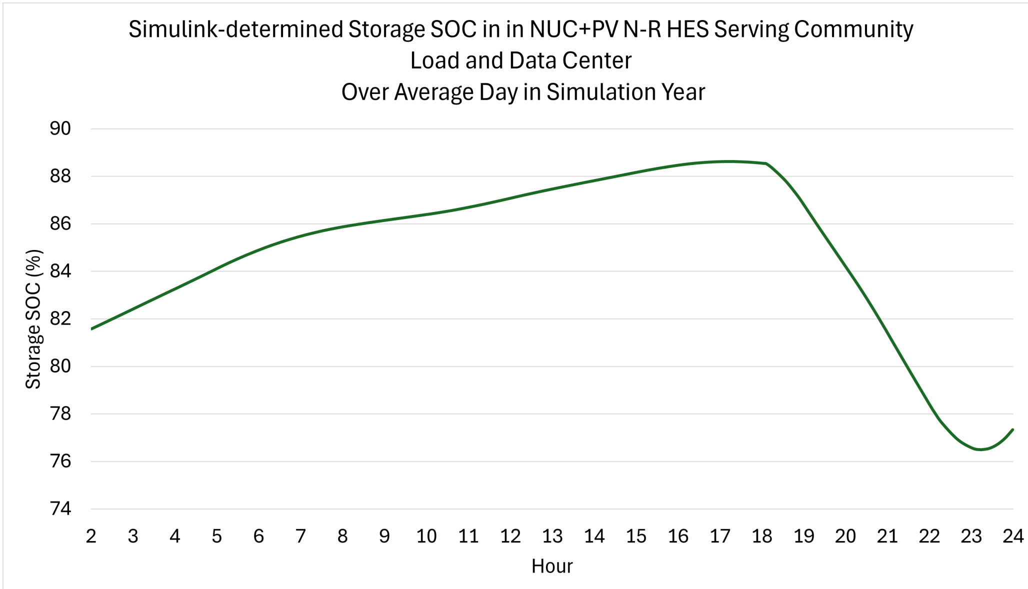
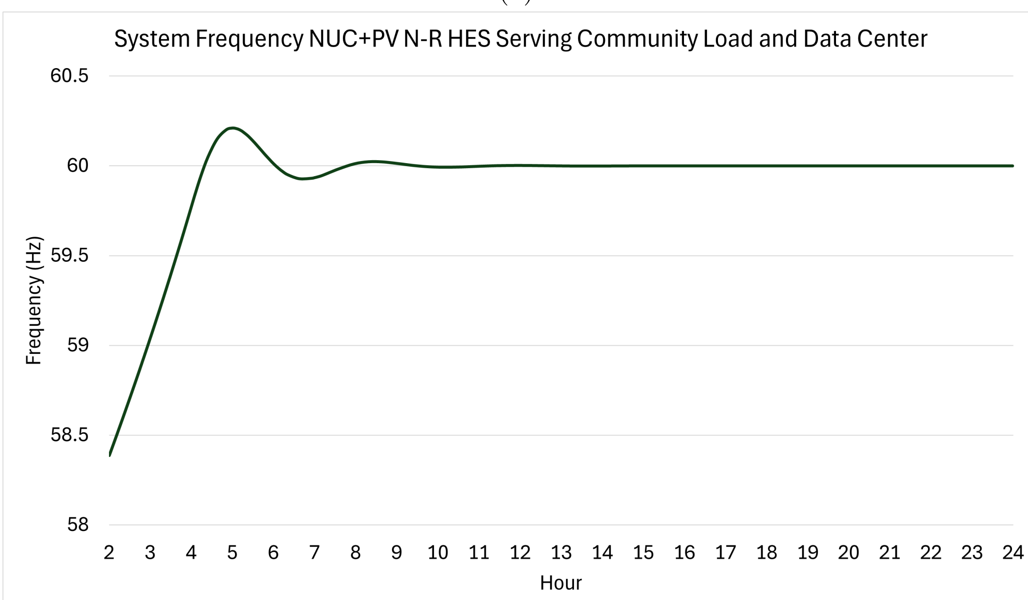


Figure 5.21: Power flows and loads served as a result of the MATLAB-Simulink model of Case Study 2 over a time average day in the simulation year. The PV power output (light pink) tracks with increased production during daylight hours. The SMR (dark pink) remains constant at 80 MW. The 50 MW data center load (orange) is constant, and the community load (lighter blue) increases throughout the day. When total electrical load demand (darker blue dash) is less than the sum of the SMR and PV generation (red dash), the storage output (green) is negative, signaling the storage system is charging. When demand exceeds SMR plus PV generation between hours 17 and 23, the storage system dispatches and power output is positive.

The MATLAB-Simulink model also calculates the storage system's state of charge based on input/output power and system efficiency. In this average day simulation, SOC ranges from 76% to 89%, which is a range expected after inspecting SOC as calculated by HOMER Pro on days when the system is not suffering from excess energy. The storage system SOC behaves as expected relative to the system's energy dispatch pattern: SOC climbs throughout the day while the battery charges, plateaus for an hour at hour 17 as the system begins to dispatch, then declines until hour 23 as energy is being dispatched from the storage system to the power loads.



(a)



(b)

Figure 5.22: (a) Storage system state of charge in Case Study 2 Simulink model (NUC + PV serving community load and data center)., (b) System frequency in Case Study 2 Simulink model (NUC + PV serving community load and data center).

The system appears to have similar issues with frequency deviations as Case Study 1, where system frequency drops below 60 Hz for the first few hours of the day, but stabilizes around 60 Hz by hour 6 (Figure 5.22b). Like in case study one, this deviation could be due to numerical calculation initialization or non-steady state behavior caused by power load startup. Future work can include investigating the cause of this frequency drop.

5.4 Analysis and Discussion of Results

This section described the use of HOMER Pro and MATLAB-Simulink software tools to model case study systems' techno-economic performance. The former tool was used primarily for economic analysis, and the latter tool was used to provide additional power flow analysis. Economic analysis provided an initial estimate of system costs, although limitations remain. The power flow models confirm that both N-R HES configurations under investigation have the potential to effectively divert energy to multiple loads, optimizing the use of both nuclear and renewable resources.

The HOMER Pro models employed a custom generator to represent nuclear in a microgrid configuration serving relevant loads alongside solar PV and thermal energy storage in Case Study 2. Tables 5.5a and 5.5b provide a summary of select economic and electrical performance characteristics calculated with HOMER Pro for Case Study 1 (NUC + PV -> Community Load + Electrolyzer based nearby Charlotte, NC) and Case Study 2 (NUC + PV + TES -> Community Load + Data Center based nearby Houston, TX), respectively. Both systems have high initial capital costs driven by nuclear, electrolyzer, and data center upfront costs. While Case Study 2 is more expensive than Case Study 1, the stakeholders considering Case Study 2 did not have costs as highest priority. Rather, criteria like technology maturity/extent of deployment were of high priority to enable rapid decarbonization, hence the decision to serve a data center over electrolyzer in this scenario.

In Case Study 1, HOMER Pro's load flow analysis functions indicate that the electrolyzer/hydrogen tank/hydrogen load configuration captures excess energy during times when the community load is satisfied. In Case Study 2, the storage system also captures excess energy and dispatches power in times of high demand; however, there

Table 5.5: Summary of HOMER Pro Results for (a) Case Study 1 (NUC + PV -> Community Load + Electrolyzer) and (b) Case Study 2 (NUC + PV + TES -> Community Load + Data Center)

(a) Summary of HOMER Pro Results for Case Study 1 (NUC + PV -> Community Load + Electrolyzer)

Parameter	Value	Unit
NPC	1.70 billion	$
CAPEX	1.12 billion	$
Operating Costs	35.8 million	$/year
LCOE	0.153	$/kWh
Peak Renewable Penetration	20.3	%
Energy Produced Over Year	728	GWh/yr
% Unmet Load	0	%
kg H_2 Produced Over Year	10.3 million	kg/yr
LCOH	10.5	$/kg

(b) Summary of HOMER Pro Results for Case Study 2 (NUC + PV + TES -> Community Load + Data Center)

Parameter	Value	Unit
NPC	2.75 billion	$
CAPEX	1.59 billion	$
Operating Costs	73.8 million	$/year
LCOE	0.263	$/kWh
Peak Renewable Penetration	68.3	%
Energy Produced Over Year	726	GWh/yr
% Unmet Load	0.056	%

are hours where excess energy exceeds the storage system's limits. Understanding a battery block was used as a surrogate for thermal energy storage, further refinement of a storage block could support improved sizing optimization to reduce excess electricity. Both systems are successful at fulfilling either all or 99.94% of the system's electric load.

Limitations exist for these models of N-R HESs in HOMER Pro. Input capital and o&M cost and performance values are currently only based on general estimates and are not based economic evaluation of a manufacturer-specific technologies. Thus, refinement of economic parameters may be needed before project budgets are finalized. Additionally, there are multiple ways to represent nuclear fuel costs in HOMER Pro.

Here, nuclear fuel costs are included as a fixed cost based on reactor burnup rate and an assumed 2 year refueling cadence, which may be sensitive to discount rate choice. Other methods include rolling fuel costs into reactor replacement costs, which could reduce sensitivity to other chosen discount rate and other economic parameters [123]. Finally, further analysis is needed to determine transmission costs, controller costs, additional infrastructure costs, and soft costs that will impact total system costs. Iterative analysis of economic parameters that get more detailed as sites and technologies are chosen and system designs are complete can lead to refined economic estimates.

While HOMER Pro does provide insights into system power flows, MATLAB-Simulink was implemented to further analyze system dynamics via its multiphysics modeling toolset. A simple microgrid model was built for both case studies to represent each N-R HES over a time-averaged day in the simulation year with the software's Specialized Power Systems library. Three phase dynamic load blocks were used to represent variable loads such as the community load and the electrolyzer, and were tuned to represent a simple storage system in Case Study 2. Static loads were represented with a Three-Phase RLC Load block. The nuclear SMR was represented via a surrogate model that used a diesel generator and governor control system. Solar PV was modeled via a three phase dynamic load block with an negative signal to represent power output instead of load. An energy storage system was implemented similarly with a three phase dynamic load block with negative signal that could absorb and dispatch energy Power load input parameters to the electrolyzer load and storage system in respective case study models were tuned so they absorbed excess energy (and in the case of the storage system, dispatch energy) and kept the SMR at full 80 MW power output throughout the day.

Analysis of the resulting power flows from the MATLAB-Simulink system models over the course of a time-averaged day in the simulation year confirm similarities between the results and those produced by HOMER Pro. In Case Study 1, the electrolyzer successfully adjusted power input to accommodate excess power production. In Case Study 2, the thermal energy storage system absorbed energy when total generation exceeds load demand, and dispatches when there is insufficient energy generated. In both models, system frequency drops below 60 Hz on startup, but begins to recover quickly and stabilizes around 60 Hz within 6 hours.

The current case study models built in MATLAB-Simulink have their limitations. They are simple models using common blocks to represent different technologies and basic control systems. These models do not investigate system disruptions or transients that might occur if loads start up or adjust in magnitude throughout the day. Furthermore, future work can also explore implementing more detailed subsystem models of each technology component in the N-R HES, such as using MATLAB-Simulink's renewables library or investigating different representations of the SMR. Further analysis that incorporates more complex system components and investigates system disruptions and transients will be important to fully understand the operational feasibility of N-R HESs.

5.5 Chapter Summary

In this chapter, the two case study N-R HESs under consideration after implementing the technology selection framework were further analyzed for techno-economic performance using HOMER Pro and MATLAB-Simulink modeling tools. Economic analysis using HOMER Pro included modifying a generic generator model to better represent nuclear energy. Results gave outcomes for system capital costs, operational costs, NPC, LCOE, and renewable penetration. This model also confirmed that each system was sufficiently able to meet required load. MATLAB-Simulink was then implemented to further investigate power flows during an average day of system performance. Models of each case study system were built as a simple microgrid. These models confirmed that excess electricity could be diverted to an electrolyzer in Case

Study 1 and confirmed the ability for a thermal energy storage system to absorb excess energy and dispatch the energy when needed in Case Study 2.

CHAPTER 6: CONCLUSIONS AND FUTURE WORK

With risks of climate change becoming apparent, nuclear-renewable hybrid energy systems are being proposed to accelerate decarbonization. These systems seek to optimize the benefits of each technology while mitigating challenges, such as the variable nature of renewable generation. As energy is generated from various technology resources, thermal or electrical energy can be diverted to multiple loads to enable efficient energy use. For example, a industrial loads or hydrogen production can be served when a primary load such as a local grid is satisfied. Stakeholders considering implementing an N-R HES must consider various factors when selecting which generation resources and end-use loads will be included in an N-R HES. In addition to economic parameters, other criteria may be of high priority, such as land use, carbon emissions, and technology maturity, and global extent of deployment for commercially mature technologies. This work presented a multi-criteria selection framework where requirements and prioritization criteria are applied to support N-R HES technology decisions. Case studies were presented to demonstrate the framework and investigate techno-economic performance.

6.1 Summary of Contributions

This thesis project presented three key contributions:

1. **Presented a novel multi-criteria selection framework for determining optimal N-R HES based on stakeholder priorities:** The proposed selection framework has a user consider exclusionary requirements and prioritized evaluation criteria, which can extend beyond economic parameters. A weighted pariwise comparison across technology options on evaluation criteria informs

selection. Relative performance of N-R HES technology options on a set of example criteria was presented.

2. **Demonstrated selection framework on two unique case study systems:** This work used two separate case study prompts with distinct requirements and criteria priorities to inform two example down-selection processes using the proposed selection framework. Starting from a smaller selection of options and evaluation criteria, Case Study 1 prioritized low costs and resulted in a system with nuclear and solar PV serving a local community grid load and an electrolyzer. Case Study 2 expanded the initial options and evaluation criteria and prioritized technology readiness. This down-selection resulted in a N-R HES with nuclear, PV, and thermal energy storage serving a local community load and a data center.

3. **Developed unique models of the case studies in HOMER Pro and MATLAB-Simulink to analyze system techno-economics:** The two software tools were used to investigate system economics and power flows, respectively. Both example systems were modeled with an 80 MW SMR and a 20 MW solar PV system serving electrical loads. HOMER Pro suggested Case Study 1 had NPC of \$1.70 billion and LCOE of \$0.153/kWh, whereas Case Study 2 had NPC of \$2.75 billion and LCOE of \$0.263/kWh. High upfront costs were drivers of overall system economics. Modeling the system via MATLAB-Simulink's Specialized Power Systems library allowed for power flow analysis and confirmation that power could be diverted to secondary loads and to and from storage systems as needed to optimize system energy use.

6.2 Future Work

Continued work can be done to expand this work on N-R HES selection frameworks to refine analysis and consider additional needs for system deployment. To further develop the proposed selection framework, the list of evaluation criteria considered across technology options could be expanded to include additional criteria. The given performance metrics across technology options will also need to be continuously updated as individual technologies mature and develop. Additionally, a more detailed performance evaluation can be performed that distinguishes technology type options. For example, stakeholders will have to determine if an HTGR or a light water SMR, or other nuclear technology type, is most appropriate for their system. Additional case studies beyond the ones presented in this work could also be considered to further investigate influence of stakeholder priorities and needs on final system selection.

There is additional work to be done to refine and expand on HOMER Pro modeling methods. For HOMER Pro modeling, input performance and economic parameters can continue to be refined. For example, continued exploration of best representation of SMR fuel costs in HOMER could be completed. Outside of the nuclear resource, transmission costs and soft cost of connecting generation resources and end-use loads can be considered in future work. Analysis of geographical impacts on technology costs can also be considered. A sensitivity analysis of different economic and performance metrics could be completed to investigate how economics are optimized in HOMER Pro such. For example, one could investigate how tuning the nuclear minimum load or adjusting the system discount rate impacts final results. HOMER Pro's thermal energy toolbox can also be explored for representing thermal loads.

Future work for the MATLAB-Simulink models include those that expand the models from the existing system setup. Studies investigating transients and faults can support understanding of practical operation. The PV, storage, and electrolyzer blocks can be expanded from being represented as three phase loads to more complex models to better capture unique technology behavior. Different generator control systems can be studied to refine modeling of nuclear power. The current model is limited to electrical power, but future work could include using the thermal energy toolbox to better model thermal energy storage or thermal loads.

Beyond model refinement, additional work is needed before N-R HESs can be deployed. Engineering integration studies are needed for practical development of these complex systems to understand transmission and interconnection needs, as well as technology needs within the power system for actively monitoring and diverting power flows. A detailed siting study will also be needed before system deployment. Future research should also investigate maintenance and operational needs and practices for these integrated systems. Finally, as these engineering studies are completed, iterative economic analysis can be performed to determine representative costs of the specific system under consideration.

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APPENDIX A: CASE STUDY WEIGHTED PAIRWISE COMPARISON MATRICES

A.1 Case Study 2 Weighted Pairwise Comparison Matrices

Tables A.1a, A.1b, and A.1c detail the weighted pairwise comparison matrices for Case Study 2, following from the discussion in Section 4.2.2. Summing across each weighted sum results in Grid + Data Center with a score of 3, Grid + Electrolyzer with a score of 0, and Grid + Desalination Plant with a score of 1.698.

The Case Study 2 generation option weighted pairwise comparison matrices is presented in Tables A.2a, A.2b, and A.2c. Summing across all normalized sums, the results give N+PV+TES a score of 3, N+PV+W+TES a score of 0.3951, and N+PV+DG+TES a score of 0.5204. N+PV+TES is the clear winner.

Table A.1: Wighted Case Study 2 End-Use Pairwise Comparison Matricies: (a), Grid + Data Center baseline, (b) Grid + Electrolyzer baseline, and (c) Grid + Desalination baseline

(a) Case Study 2 End-Use Pairwise Comparison Matrix (Grid + Data Center Baseline), weighted

	Grid + Data Center	Grid + Electrolyzer	Grid + Desal Plant
Capital Costs	0	0.0949	0.0949
O&M Costs	0	0.0949	-0.0949
Land Use	0	-0.1679	-0.1679
Carbon Emissions	0	0	0
TRL/Deployment Extent	0	-0.4088	0
Sum	0	-0.3869	-0.1679
Normalized Sum	1	0	0.566

(b) Case Study 2 End-Use Pairwise Comparison Matrix (Grid + Electrolyzer Baseline), weighted

	Grid + Data Center	Grid + Electrolyzer	Grid + Desal Plant
Capital Costs	-0.0949	0	-0.0949
O&M Costs	-0.0949	0	-0.0949
Land Use	0.1679	0	0
Carbon Emissions	0	0	0
TRL/Deployment Extent	0.4088	0	0.4088
Sum	0.3868	0	0.2190
Normalized Sum	1	0	0.566

(c) Case Study 2 End-Use Pairwise Comparison Matrix (Grid + Desalination Baseline), weighted

	Grid + Data Center	Grid + Electrolyzer	Grid + Desal Plant
Capital Costs	-0.0949	0.0949	0
O&M Costs	0.0949	0.0949	0
Land Use	0.1679	0	0
Carbon Emissions	0	0	0
TRL/Deployment Extent	0	-0.4088	0
Sum	0.1679	-0.2190	0
Normalized Sum	1	0	0.566

Table A.2: Weighted Case Study 2 Generation Pairwise Comparison Matrix: (a) N+PV+TES baseline, (b) N+PV+W+TES baseline, and (c) N+PV+DG+TES baseline

(a) Case Study 2 Generation Pairwise Comparison Matrix (N+PV+TES baseline), weighted

	N+PV+TES	N+PV+W+TES	N+PV+DG+TES
Capital Costs	0	-0.0949	-0.0949
O&M Costs	0	-0.0949	-0.0949
Land Use	0	-0.1679	-0.1679
Carbon Emissions	0	0	-0.2336
TRL/Deployment Extent	0	0	0
Sum	0	-0.3577	-0.5912
Normalized Sum	1	0.3951	0

(b) Case Study 2 Generation Pairwise Comparison Matrix (N+PV+W+TES baseline), weighted

	N+PV+TES	N+PV+W+TES	N+PV+DG+TES
Capital Costs	0.0949	0	0.0949
O&M Costs	0.0949	0	0.0949
Land Use	0.1679	0	0.1679
Carbon Emissions	0	0	-0.2336
TRL/Deployment Extent	0	0	0
Sum	0.3577	0	0.1241
Normalized Sum	1	0	0.3469

(c) Case Study 2 Generation Pairwise Comparison Matrix (N+PV+DG+TES baseline), weighted

	N+PV+TES	N+PV+W+TES	N+PV+DG+TES
Capital Costs	0.0949	-0.0949	0
O&M Costs	0.0949	-0.0949	0
Land Use	0.1679	-0.1679	0
Carbon Emissions	0.2336	0.2336	0
TRL/Deployment Extent	0	0	0
Sum	0.5912	-0.1241	0
Normalized Sum	1	0	0.1734

APPENDIX B: INPUT PARAMETERS FOR MATLAB-SIMULINK N-R HES CASE STUDY MODELS

Section 5.3 describes how MATLAB-Simulink was used to model the two case study N-R HES systems. Tables B.1 and B.2 detail the input parameters for solar PV output and community load for each respective case study model. Values were calculated by averaging each hourly value over the course of the year. For example, the community load at hour 1 on each day of the year was averaged to find the value used in the MATLAB-Simulink model for hour 1.

Table B.1: Case Study 1 input parameters for community load and PV output in MATLAB-Simulink model

Hour	Average Community Load (W)	Average PV Output (W)
0	7,718,378	0
1	7,566,608	0
2	7,497,145	0
3	7,543,977	0
4	7,418,544	0
5	11,105,385	40,395
6	18,104,701	426,318
7	25,188,450	2,242,119
8	28,876,225	4,934,099
9	29,603,075	7,271,003
10	29,242,125	9,106,357
11	28,951,001	10,012,513
12	29,533,337	10,308,543
13	29,535,006	9,795,115
14	28,994,238	8,434,190
15	29,276,826	6,488,097
16	32,792,216	4,242,929
17	36,499,193	1,729,581
18	43,328,807	287,458
19	42,960,971	21,045
20	44,040,424	0
21	43,870,543	0
22	33,024,783	0
23	18,528,040	0

Table B.2: Case Study 2 input parameters for community load and PV output in MATLAB-Simulink model

Hour	Average Community Load (W)	Average PV Output (W)
0	9,033,846	0
1	7,873,035	0
2	7,341,748	0
3	7,699,945	0
4	6,740,571	0
5	11,754,913	19,512
6	17,668,058	461,897
7	24,404,312	2,438,062
8	28,280,409	4,751,920
9	30,267,235	6,932,265
10	29,244,286	8,633,124
11	28,468,771	9,459,516
12	30,062,848	9,699,079
13	30,049,575	9,200,576
14	28,612,127	7,897,322
15	29,294,889	6,046,253
16	32,633,731	3,936,865
17	36,439,546	1,668,400
18	42,740,687	224,702
19	41,944,281	0
20	44,305,450	0
21	43,884,476	0
22	33,223,348	0
23	19,231,915	0